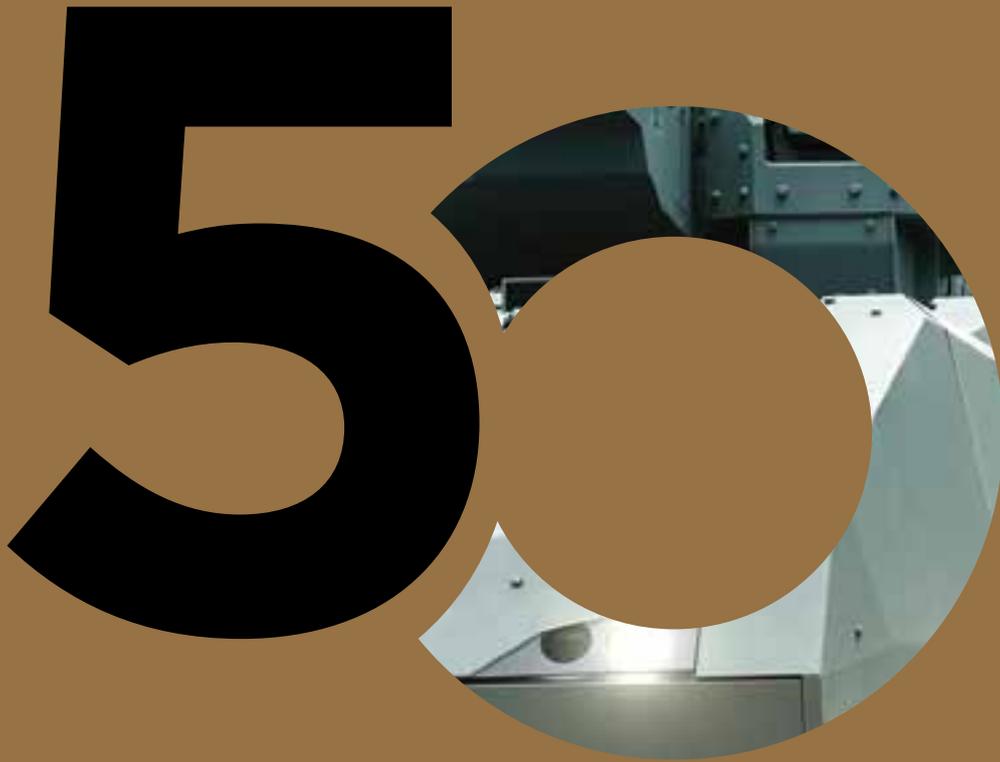


ENGINEERING LAND SYSTEMS



*“DTC IS THE
SECRET-EDGE
WEAPON OF
THE SAF”*

DR NG ENG HEN
MINISTER FOR DEFENCE



ENGINEERING SINGAPORE'S DEFENCE — THE EARLY YEARS



DTC IS THE SECRET-EDGE WEAPON OF THE SAF



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FOREWORD



The journey of Singapore's Defence Technology Community (DTC) parallels that of the Singapore Armed Forces (SAF) – indeed both were co-dependent and iterative processes which fed off each other's success. Pioneers in both communities recognised very early on the stark limitations of a small island with no geographical depth and limited manpower. But despite this realisation, they were undaunted and shared a common resolve to mitigate Singapore's vulnerabilities and constraints, and build a credible SAF through sheer will, commitment and the harnessing of the powers of technology. In Dr Goh Keng Swee's words, "we have to supplement the SAF's manpower with new technology, as manpower constraints will always be there. Our dependency should be more on technology than manpower. And we must develop indigenously that technological edge." As worthy and important as these ideals were, it was an arduous journey for the DTC. With poor standards of general education, let alone engineers or scientists, how could Singapore develop such capabilities?

This book series chronicles the last 50 years of that ascent that began in 1966. The DTC has indeed come a long way from its humble beginnings and with it, a transformation of the SAF's capabilities. Today, both the SAF and the DTC are respected professional bodies and the requests from advanced economies to collaborate reflect the standards which we have achieved. Our closely-knit community of defence

engineers and scientists stands at the frontier of technological progress. Indeed the DTC is the secret-edge weapon of the SAF.

As the DTC celebrates its 50th anniversary, we want to thank especially its pioneers who were committed to achieve the unthinkable and were not daunted by severe challenges along the way. Their efforts and beliefs have spawned world class agencies such as DSTA and DSO, and the family of Singapore Technologies (ST) companies.

More hearteningly, the virtuous effects extend into mainstream society too. Today the defence cluster of DSTA, DSO, MINDEF, the SAF and ST employs the largest proportion of scientists and engineers in Singapore – almost one in every 12! It is not an overstatement that these entities have been the main receptacles to maintain the science and technology capabilities in our nation, providing life-long careers in the process.

Beyond defence, the DTC has also positively impacted our society in a variety of ways: in producing mass thermal scanners to combat the 2003 SARS outbreak, in designing and building the iconic Marina Bay Floating Platform to host the National Day Parades and sports events, in breaking new ground and old mindsets when we built the underground storage for munitions, in forming the nucleus to start the MRO (maintenance, repair and overhaul) industries to service airlines in Singapore and globally.

The stories that are told in this book series chronicles should lift the spirits of Singaporeans, old and young. They celebrate what pioneers and successive generations of committed scientists and engineers have accomplished over the years. But they also give hope to our future, as they will serve as reminders during difficult times to overcome challenges and continue to keep Singapore safe and secure for many years to come.

A handwritten signature in black ink, appearing to read 'Ng Eng Hen'.

Dr Ng Eng Hen
Minister for Defence
Singapore

MESSAGE



The Defence Technology Community (DTC) has steadily evolved over the last 50 years. We started off as a small, three-man technical department in the Logistics Division in 1966 supporting defence equipment procurement and there was much work to be done. The Army then was largely equipped with second-hand vehicles and surplus equipment left by the British. The Republic of Singapore Navy (RSN) had two boats, one steel and the other wooden. Recognising the need to overcome the immutable challenges of geography and resource constraints facing Singapore, we extended our scope to include conceptualisation, development and upgrade of defence systems. These efforts leverage the force multiplying effects of technology to meet the unique challenges and operational requirements of the Singapore Armed Forces (SAF), beyond what could be had buying off-the-shelf.

This four-book “Engineering Singapore’s Defence – The Early Years” series covers the entire spectrum of the DTC’s work in the land, air and sea domains to deliver cutting-edge technological capabilities to the SAF. It chronicles our 50-year journey and documents the largely unheard stories of our people – their challenges, struggles and triumphs, their resolve and ingenuity, and their persistence in overcoming the odds. These stories include:

- The upgrading of the French-made AMX-13 light tank to the AMX-13 SM1 configuration by the DTC, the Army and ST Engineering, laying the foundation for the design, engineering and production of the Bionix, Bronco and Terrex armoured fighting vehicles for the Army.

- The integration of the RSN’s missile gunboats and missile corvettes which built up the DTC’s confidence to move on to specify and acquire best of breed systems to integrate into new ships like the frigates. It also laid the foundations for ST Engineering’s capabilities to design and build ships for the RSN and some other navies.
- The conversion of old US Navy’s A-4 Skyhawk aircraft into the A-4SU Super Skyhawk for the Republic of Singapore Air Force, building up ST Engineering’s capabilities to undertake further aircraft upgrades such as for the F-5E Tiger fighter aircraft, and to undertake servicing and repair of commercial aircraft.
- The system-of-systems integration efforts to evolve the island air defence system, building on legacy systems left by the British to seamlessly incorporate new weapons, sensors, and indigenously developed command and control systems to extend the range and coverage of Singapore’s air defence umbrella, and the build-up of the DTC as a system-of-systems to deliver cutting-edge capabilities and systems to the SAF, and to meet the technology requirements of the nation.

While not exhaustive, these stories provide us with a glimpse of the “dare-to-do” and enterprising spirit that our DTC personnel and forerunners possess.

There is no end to change and transformation. Singapore and the SAF will continue to face many challenges in the years ahead. However, with the capabilities and expertise developed over the years in its more than 5,000-strong personnel, and its established linkages with

renowned R&D partners locally and around the world, I am confident that the DTC will remain steadfast in delivering the critical technologies and innovative solutions for the SAF and the nation. May the stories in these books inspire our current and future defence engineers and scientists to continue to push boundaries and think creatively to deliver capabilities that will safeguard our sovereignty for the years to come.

A handwritten signature in black ink that reads "Ng Chee Khern". The signature is fluid and cursive.

Mr Ng Chee Khern
Permanent Secretary (Defence Development)
Ministry of Defence, Singapore

PREFACE



Critical to the build-up of the Singapore Armed Forces (SAF) was logistics. Equipment and stores needed for training had to be purchased and issued to units before training could begin. The trainees would need to be clothed in uniforms and equipped with their personal equipment, housed in barracks, provided with their personal weapons and transportation, and most importantly be fed four to five times each day to prepare for the vigorous training. The Logistics Division in the Ministry of Interior and Defence (MID) carried out this task with officers recruited as Short Service Commission Officers. They learnt about logistics by doing. Tenders for the supply of equipment and stores were called each day, and contracts and procurement orders issued as soon as the completion of evaluation of the offers. Preparation of specifications for the procurement and testing of samples

provided by tenderers were major tasks for each purchase. Acceptance tests were conducted to ensure the materials supplied were in accordance with the specifications before the various logistics bases would take them into inventory for issue to the units.

Chapter 1 is an account of the development of technical capability in the Logistics Division which began with the testing and evaluation of equipment and stores for the training schools located in Singapore Armed Forces Training Institute (SAFTI) and the first two National Service (NS) battalions. The planned development of the SAF and MID was disrupted by the decision of the UK Government to withdraw all troops from Singapore by 1971. We had three years to build an army, air force and navy and the logistics and engineering organisations for their support. Graduates in engineering and science enlisted into NS were tasked with the responsibility to provide technical support for the rapid development of the three arms of the SAF.

Chapter 2 describes the development of technical capabilities in our defence industries to provide armament for the SAF. The strategy of integrated armament development would provide the SAF with operational capabilities greater than those that could be purchased from overseas. The clear focus on engineering and the development of leading edge armament, tempered with the need for economic viability, drove the growth of our defence industries. Personal accounts by former engineers of the Chartered Industries of Singapore (CIS) showed the courage and technical capabilities of our armament engineers.

Chapter 3 describes the development of 155mm artillery, the backbone of the firepower of our Army. Engineers in Ministry of Defence (MINDEF), CIS and Ordnance Development and Engineering of Singapore (ODE), after one decade of experience in the development and production of armament for the SAF, were ready to make a major leap into the development and production of 155mm howitzers. They had the confidence of developing 155mm howitzers that would best meet the needs of the Army and at a total life cycle cost lower than that produced by established armament manufacturers from overseas.

Chapter 4 is an external view by a very respected expert on military matters and land warfare on the growth of the engineering and development capability of armoured fighting vehicles for our Army.

Chapter 5 is a contribution from key members of the research and development team of Singapore's first driverless vehicle, a M113 armoured personnel carrier named Ulysses by the project team. The principal investigator was from the Singapore Institute of Manufacturing Technology (SimTech) and members of the project team included engineers from the Defence Science and Technology Agency (DSTA) and ST Kinetics. This chapter shows the daring of engineers to increase the combat capability of our future armoured fighting vehicles through automation, information, precision and integration.

Chapter 6 is the perspective from very knowledgeable users of technology – officers of the Signal Formation. They wrote on the growth of the command and control capability

of fighting units in the Army from the early days of line and wireless communication devices, to the digital command, control, communications and computers system-of-systems.

Chapter 7 is an account of the technical challenges in the planning, design and engineering of operational infrastructure facilities for the SAF. The capability to design, test and evaluate, and construct passive protection measures was also used to support the Ministry of Home Affairs in the planning and design of Civil Defence Shelters for the protection of our civilian population from weapon effects.

Chapter 8 is the last chapter of this book on the creation of underground space in rock caverns for the storage of ammunition in the SAF's Underground Ammunition Facility (UAF) at Mandai. The chapter shows the life cycle approach in the planning, from conception to operation, technology development through computer simulation model, small-scale testing and large-scale testing and collaboration with the best engineers in the world in the development and operation of ammunition facilities. This project was groundbreaking as it showed that Singapore could more than double the amount of usable space with the development of underground rock caverns.

A handwritten signature in black ink, appearing to read 'Lui Pao Chuen'.

Prof Lui Pao Chuen
Editor, Engineering Land Systems

THE BEGINNINGS OF DEFENCE LOGISTICS AND ENGINEERING

This chapter serves two purposes: to provide an introduction to the subjects that will be covered by this book, and to record some of the early developments of defence science and technology in Singapore.

At Singapore's independence on 9th August 1965, the Singapore Police Force (SPF) was a well-established force with a proud tradition in the maintenance of law and order. It had 6,700 Regulars, and 1,300 Guard and Escort personnel. The SPF was also supplemented by some 1,200 Volunteer Special Constables. It was well-organised with a command structure, officers and men. Many young school-leavers would aspire to join the SPF to be inspectors, if they had a Higher School Certificate, the equivalent of an "A" level education. The SPF had a training school for basic, advanced and higher-level training for constables and officers. The Senior Police Officers' Mess at Mount Pleasant was the institution for informal learning and socialising for senior police officers. The Police Reserve Units and the Criminal Investigation Department (CID) had also generated many police officers with outstanding leadership qualities.

The SPF came under the command of the Ministry of Interior and Defence (MID), together with the fledging Singapore Armed Forces (SAF). The SPF logistics units for vehicle repair, radio repair and weapons repair became logistics bases of the SAF. They were named Vehicle Repair Base, Electronics Supply and Maintenance Base, and Weapons, Ammunition and Optics Base (WAOB) respectively.

The Radio Division located in Lower Barracks at Pearl's Hill provided communications

support for the SAF. Rooms at Lower Barracks were converted into offices for MID. The Combined Operations Room located in Upper Barracks at Pearl's Hill became the operations room of MID. With the staff expansion in MID, more office space was needed. The Upper Barracks was subsequently also converted into MID's offices.



Pearl's Hill Upper Barracks, circa 1945

First SAF Build-up Plan

The first plan for the build-up of the SAF prepared soon after Singapore's independence set out the details for the organisation of MID, and the tasks required to raise an ORBAT (order of battle) of 12 battalions for defence and internal security operations. The 12 battalions were:

- seven infantry battalions
- two recce battalions
- one engineer battalion
- one artillery battalion
- one commando battalion

Raising an Army

Crucial to the success of the plan was the availability of manpower with the qualities necessary to make good commanders and soldiers. The first task was to train a cadre of instructors for the Singapore Armed Forces Training Institute (SAFTI) which was established on 14th February 1966.

By mid 1966 MID concluded that it would not be possible to recruit the number of officers and soldiers needed for the 12 battalions. The government took the very difficult decision to

introduce National Service (NS). SAFTI would need to be expanded to accommodate the large number of trainees that would be called up for NS, and found suitable to be trained as NCOs (non-commissioned officers) and officers.

The first Director of SAFTI, Lieutenant Colonel (LTC) Kirpa Ram Vij, was a lieutenant in the Singapore Volunteer Corps (SVC) and a Principal Assistant Secretary in the Ministry of Finance as its Head of Organisation and Methods. He was appointed LTC on 15th February 1966 upon the commencement of the preparatory course. The SPF provided the best field commanders they had in service for the preparatory course. They were Deputy Superintendent of Police (DSP) T.E. Ricketts, DSP R.A. Lawrence, DSP Richard Tay, DSP Wilfred Skinner (then goalkeeper of the national football team) and Inspector Chin Chee Chean. Senior in age and rank to the trainees, they were remembered for their keen understanding of human nature and generosity in sharing their knowledge of leadership with the younger members of the preparatory course.

Israel sent a team of five advisors to assist in the preparatory course. As the camp at Pasir Laba was being constructed, the base camp of the preparatory course was at Jurong Town Primary School. Each day the trainees would ride in British-made Bedford trucks to the Pasir Laba Live Firing Area for their training. COL (Ret) Goh Lye Choon remembered fondly that Permanent Secretary for MID (PS(MID)) George Bogaars had spent much time in the field during the preparatory course. He had also resolved problems between the Israeli team and regular army officers who had found the training with the self-loading rifle and individual field crafts to be a repetition of what they had already knew.



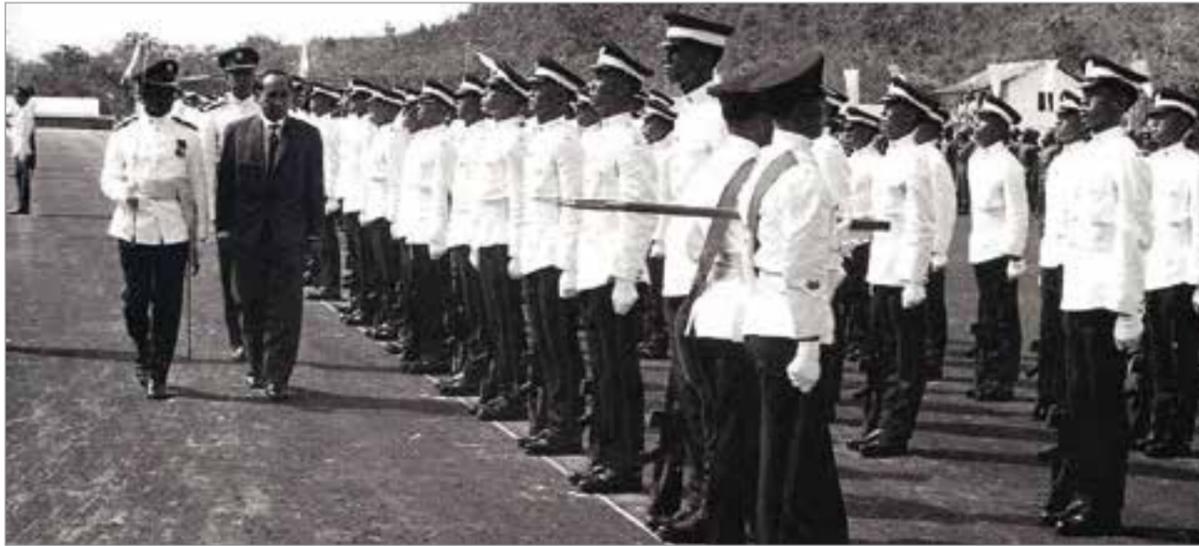
Entrance to SAFTI, circa 1966

On completion of the preparatory course, each graduate received a hard-earned certificate from Dr Goh Keng Swee himself at a graduation ceremony on 7th May 1966. Younger officers like LTA Goh Lye Choon were promoted to the rank of captain (CPT) and became platoon commanders (PC) for the first training course at SAFTI. There were two training companies with Major (MAJ) John Morrice in command of A Company and DSP T.E. Ricketts in command of B Company. Training of the first batch of recruits began on 1st July 1966 with 150 recruits in each company. They were accommodated in the newly-completed wooden barracks of the SAFTI camp.



Dr Goh Keng Swee, then Minister for Interior and Defence, and LTC Kirpa Ram Vij, then Director SAFTI at the opening of SAFTI, on 18th June 1967

SAFTI was the first military camp construction project of the SAF. It was completed in a matter of months to meet the start of the first training course. The top architect of the Public Works Department (PWD), Mr Lim Soon Chye was assigned to be the Senior Architect (Defence). He and his team of PWD



Passing-Out-Parade of the 1st SAF Officer Cadet Course with 117 graduates on 16th July 1967

engineers worked tirelessly to build the SAFTI camp which was declared open on 18th June 1967 by Dr Goh Keng Swee, then Minister for Interior and Defence, about one month before the Passing-Out-Parade of our first batch of 117 SAF officers on 16th July 1967.

The National Service (Amendment) Act was passed on 14th March 1967. The first batch of recruits was called up in August 1967 for NS.

Two new battalions, 3 and 4 SIR, would be raised with the officers and NCOs who graduated from SAFTI as commanders. The Commanding Officer (CO) of 3 SIR was MAJ Richard Jambu and the CO of 4 SIR was MAJ T.E. Ricketts (seconded from the SPF). The camps for these two battalions were under construction on the reclaimed land at Bedok. Despite the best efforts made by PWD, these camps could not be ready for the first intake of full-time National Servicemen (NSFs). Flats at Taman Jurong were converted into temporary barracks to accommodate the recruits.

A parallel construction project was the conversion of the passenger, cargo and office buildings of the disused Kallang Airport into the Central Manpower Base (CMPB) for the processing of NS enlistees. MAJ Tan Hup Seng was the officer in the Logistics Division

to work with PWD for the construction of camps and military facilities. A fresh electrical engineering graduate, Mr Wan Siew Kay, then serving NS, was assigned to work with him.

As there were no Singaporeans experienced in raising an army, civil servants, teachers, police officers, volunteer officers in the SVC, regular officers from 1 and 2 SIR were deployed to staff MID departments and installations. Many SPF officers and Administrative Officers who were then in service with the former Ministry of Home Affairs also continued their service in MID.

As the first Director of SAFTI, LTC Kipa Ram Vij and his staff had to study all the training doctrine materials that the Israeli advisors had brought with them to decide which of the doctrines would be relevant to the SAF. Warfare in large areas of the desert would not be the same as the terrain that the SAF would be operating in.

There were a number of guiding principles that did not depend on terrain, like the value of surprise. Operations security would be of critical importance to achieve surprise at the strategic, operational and tactical levels. The appearance of an SAF force in an area that the enemy was not prepared for would be decisive

in battles. The mobility of infantry battalions by foot over close terrain and crossing of water obstacles without the need to build bridges and prepare flotation devices was highly valued. Our soldiers must therefore be physically very fit and trained for long marches with full battle order.



Officers attending the Peoples' Defence Force Officers' Orientation Course in 1968

Ministry of Interior and Defence

The first Director of General Staff was Assistant Chief Commissioner of Police, Mr Tan Teck Khim, who later became the Commissioner of Police. Other SPF officers who served in MID and the SAF included Mr Michael Thoo, the first Chief of Communications and Electronics and Mr Sahari, the first CO of WAOB. Mr Derrick De Souza served under the Director of Logistics and Mr Reggi Sandosham served in the General Staff Division. Mr Lim Choon Mong was a department head in the Manpower Division. Mr T.S. Zain, Assistant Superintendent of Police (ASP) and Officer-in-Command (OC) (Office Administration & Security), looked after the whole MID. Mr Zain rostered MID officers for duties as duty staff officers. Mr Cecil Cooke and Mr Tan Chin Hwee served under Mr Tay Seow Wah in the Security and Intelligence Division.

General Staff Division and Combat Means Committee

The General Staff Division was responsible for planning, force development and operations.

There were four departments in the General Staff Division: Organisation, Training, Operations, and Communications and Electronics. The Combat Means Committee comprising General Staff officers, Senior Specialist Staff Officers (SSSO) and Head Technical Department, Logistics Division would recommend adoption of operational requirements to the Director of General Staff. As operational requirements were critical to the acquisition of weapon systems, a systems study would be necessary with the use of Operations Research (OR) as a tool. OR was developed in the United Kingdom (UK) and US during World War II to use scientific methodologies to solve operational problems, for example, the determination of the depth at which depth charges should be detonated in the prosecution of submarines.

A newly-graduated mechanical engineer, Mr Henry Cheong, was enlisted as the staff officer to address force development issues like the analysis of operation requirements and their solutions. He was the secretary of the Combat Means Committee. He was sent to UK Ministry of Defence to learn OR and spent a year learning how the British Army, Royal Navy and the Royal Air Force (RAF) used OR in the planning of their future operational capabilities. He was the first Weapon Staff Officer of the SAF.

Logistics Division

The Logistics Division was responsible to clothe, equip, house and feed the constant flow of recruits enlisted for NS, and to support the procurement of training stores for SAFTI, School of Artillery and School of Engineers. Procurement was the top priority activity of the Logistics Division.

The first Director Logistics, Mr DF Collins, was posted into MID from the Central Supply Office to lead the procurement of equipment and stores for the SAF. It was a mad rush to purchase all the materials that would be required for training to begin on 1st July 1966

at SAFTI. Dr Goh Keng Swee had directed that the training must commence as scheduled and to sort out the logistics and manpower problems along the way.

Dr Goh Keng Swee had set out very clearly the division of responsibilities between the SAF, MID and Chartered Industries of Singapore (CIS) in the development of our defence capability. The SAF would plan, train and operate the armed forces. MID would be responsible for manpower, logistics and finance. CIS would produce ammunition and weapons for the armed forces.

Mr Ong Kah Kok, who was the first Director of People's Association, was posted to MID in early 1966 and reported directly to Dr Goh Keng Swee to implement special projects. The special project that had the highest priority was the organisation of our first National Day Parade on 9th August 1966. There was no precedence in the organisation of such a large event in Singapore. Mr Ong Kah Kok had to draw on all his connections in the Public Service and MID to pull off the event. In June 1966, He succeeded Mr D.F. Collins as Director Logistics and remained in that appointment until December 1973. During his tenure he was the man behind all the contracts signed for the procurement of equipment for the SAF.

The procurement process would begin with an SSSO of the General Staff Division providing a statement of stores and equipment needed for new units that would be raised. The Logistics Division would prepare the scale of equipping and tables of entitlement for each unit. The provisioning staff would then consolidate the requirement for each item and prepare a requisition list with the quantity for tendering. The tender document would include the description or specifications of the items to be supplied. The equipment for training aids proved to be the most difficult to purchase as most of the items needed had to be designed and then manufactured.

The writing of tender specifications for the procurement of equipment and supplies for the Army was the responsibility of the Test and Evaluation Section of the Logistics Division. This section also had the responsibility to test and evaluate samples submitted in the tender, and to accept deliveries into the logistics bases. The name of the section was soon changed to Test, Evaluation and Acceptance (TEA) Section to reflect the function it had to perform to inspect and accept all stores and equipment purchased by the Logistics Division for the SAF.

Actuation Department

The most powerful man in the Logistics Division next to Director Logistics was COL Minjoot, Head of Actuation Department. He held the highest rank of colonel in the Volunteer Corps and was highly regarded by all. He commanded all the SAF logistics bases and units, and had complete authority to decide on the priority of allocation of equipment, supplies, transport and maintenance services. He was the SAF's first G4 Army. He was very well supported by an adoring staff, LTA Hamid Khan, who was known by everyone in the SAF as the man to turn to for supplies, from "Herbert Johnson" peak caps to jungle boots.

"The person I remembered most is LTA Hamid Khan. Being an experienced quartermaster, he was able to control the requisitions from the various units' quartermasters lining up each morning to request for stores. He was also very resourceful, able to beg, borrow, or mobilise equipment when needed urgently for parades or ceremonies. He was the man COL Minjoot relied on when in tight situation. I recall that LTA Hamid Khan was the first WO1 to be promoted to Second Lieutenant."

- LTA Seow Tiang Keng, an engineering graduate who had served as the 2IC in the TEA Section.

Though feeding of the troops in the field was very important, feeding "A", "B" and "C"¹ vehicles with fuel and weapons with ammunition were equally important. Equipment would also break down in the field, which required field maintenance. Quick repairs of minor battlefield damages would help in the recovery of a unit's operational capability after a hard-fought battle.

Field logistics was thus planned as an important operation to sustain the operational capability of SAF units and as a force multiplier. Engineers and technicians contributed directly to the fighting capability of the SAF through field logistics.

Actuation Department evolved into G4 Army and eventually became a department of the General Staff in 1975.

Inspectorate Branch, Organisation and Control Department

The Logistics Division also had the responsibility to ensure that the equipment would be operated and maintained in accordance with the procedures spelt out in the technical manuals. As this function was important, the Inspectorate Branch was established in the Organisation and Control Department. The TEA Section became a section of this new branch.

By early 1969 there was a nagging concern that the logistics administration in the SAF units could be better managed. There had been no systematic stock-check to verify that all stores were properly accounted for. To prevent stores from being moved between storehouses during inspection to cover shortfalls, all units in the same area would be inspected at the same time. There were seven major units like SAFTI and logistics bases, 13 battalion size units and nine minor units. The inspection

¹ Standard terms used in the SAF. "A" and "B" vehicles refer to armoured vehicles and soft-skinned vehicles respectively. "C" assets refer to engineering plants.

was carried out over a period of four months with 10 teams. Each team consisted of four officers and 12 other ranks.

The data collected from the inspections was of great assistance to the managers of the inventory control system and maintenance system of the SAF.



Christmas eve party of the Technical Department to mark a very busy year supporting the acquisition of weapons and materials for the SAF, 1969

New Force Build-up Plan after the Announcement of UK Troop Withdrawal by 1971

After 3 and 4 SIR were raised in September 1967, there was a perceptible sigh of relief in MID. Life could not be worse than the crazy times that MID had gone through in the previous 12 months to build training schools, train officers and buy equipment for the Army. This calm was just before the storm which struck us in January 1968.

On 15th January 1968, the UK Government announced that all its forces would withdraw from Singapore by December 1971. There was less than four years to build the SAF to deal with threats from the land, air and sea. Two infantry battalions had just been formed and the support arms, Artillery, Engineers and Signals, had just started. Effort to raise two recce battalions was still being planned.

The basic premise in the plan for the development of the SAF was that the British would not withdraw its forces before 1975. The plan for the SAF's ORBAT development would begin with land forces, followed by air and naval forces. Air defence would be provided by the RAF with their Lightning supersonic interceptors at Tengah, the Air Defence Radar Unit at Bukit Gombak, and the squadron of Bloodhound surface-to-air missile systems at Seletar.

To allay our fear of not having an air defence umbrella, the UK agreed to provide the following assistance:

- Transfer the Air Defence Radar Unit and Bloodhound surface-to-air missile squadron to Singapore
- Sell Rapier to Singapore, if asked
- Sell Hunter Mark 6 fighter aircraft to Singapore after 1970
- Train Singaporean fighter pilots
- Turn over RAF airfields to Singapore by 1972

The 12-battalion ORBAT of the SAF was being raised as fast as manpower resources were made available. Mechanisation was needed to increase the capability of the SAF. This could be done with the building of one armoured brigade with the manpower resources that had been planned for the two recce battalions, and to convert one active and one reserve infantry battalion into two armoured infantry battalions. The range of the 120mm mortar would not be sufficient to support the armoured brigade and howitzers would be needed for the artillery battalions. Signal battalions with longer-range communication capability would be needed for the new SAF ORBAT. Field logistics units would be needed to sustain the combat units in the field.

The organisation and establishment of MID was based on the plan to raise an ORBAT of 12 battalions and logistics bases. However, it was grossly inadequate in supporting the

planning and development of the land, air and sea forces.

There was an urgent need to establish an Air Staff and a Naval Staff to plan and drive the force development in these two domains. The concept of the SAF as one single service would require the Air Staff and Naval Staff to come under the General Staff Division in MID. The first task for the General Staff Division was the preparation of a new plan for the development of the new ORBAT.

Strengthening Technical Capability in MID

The Logistics Division needed to be strengthened with additional staff in each of the departments and logistic bases. A new department, the Technical Department, was established in July 1968 as the fourth department to lead in the procurement of complex weapon systems like tanks, fighter aircraft and combat ships, and to develop the engineering and logistics support for training and operations. The mission of the Technical Department was to provide technical support in the purchase of equipment, prescribe specifications and standards for their maintenance after introduction into service.

The staff of the Inspectorate Branch and TEA Section formed the core of Technical Department. The technical staff of seven comprised, a Physics graduate CPT Lui Pao Chuen, a Chemistry graduate LTA Chye Wee Seng and an Engineering graduate LTA Seow Tiang Keng, and four second lieutenants (2LTs) from the first batch of Service Officer's Course.

The second Service Officer's Course was completed in January 1969. Six engineers joined the department.

The head count went up to 13 officers and 16 other ranks. The 13 officers also served in the Inspectorate Branch concurrently. The

new weapon systems to be acquired for the proposed ORBAT required plenty of money, technical manpower and training space for the armoured brigade and the air forces.

The budget for defence rose to around 6% of the GDP. Hundreds of engineers and technical officers, and thousands of technicians were needed. The training of technicians paralleled the training of SAF combat vocationalists. An institute for the training of technicians, the SAF Technical School (SAFTECH), was established at Seletar Air Base. Mr Foo Kok Swee was appointed Director of SAFTECH and Commander of Seletar Air Base, and given the rank of LTC.

As the delivery lead-time for major equipment would take more than 24 months after order, the build-up plan required early decisions, within two years from 1968, for major ORBAT equipment like:

- Fighter aircraft
- Surface-to-air missiles
- Anti-aircraft artillery
- Helicopters
- Armoured personnel carriers
- 155mm artillery
- Communication equipment and systems
- Missile gun boats

The Manpower Division had the hardest task of recruiting staff with relevant working experience from the private sector as SSC officers to lead the young officers that would be available through NS. As all university graduates and newly employed officers in the Civil Service were liable for NS, MID had the entire cohort of university graduates deployed to staff MID and SAF units.

As SAFTI was already operating at maximum capacity, it could not train all available graduates to be officers. Some graduates would be serving their NS part time in the PDF and the SPF, and some were not even called up for NS. This created an enormous

morale problem as the graduates serving full-time were only paid NS allowance and served in appointments that they did not think would enhance their careers.

National Service, as perceived by National Servicemen, LTA (Ret) Sia Chong Hean

In the rapid build-up of the SAF in the late 1960's following the announcement of withdrawal of British troops from Singapore, graduate NS officers felt most unhappy and perceived an unfair treatment among them. Although all fresh graduates, new civil servants and returned scholars were liable to be called up, not all were enlisted into full-time NS. Firstly, there was limited capacity at SAFTI to accommodate all the graduates as trainees, and secondly, to sustain the rapid industrialisation programme and related service sectors required, a proportion of quality graduates. Hence, quite a number who were liable were only serving part-time PDF or SPF duties. There was a vast disparity in the treatment, both in terms of training and pay, when graduate NSFs undergoing training in SAFTI compared with their contemporaries outside. The monthly allowance for an NSF was only \$90 per month, versus a fresh graduate's average salary of \$750 per month, with some being paid as much as \$1,000 per month working outside. The harsh training NSFs received at SAFTI as compared to sheltered lives of their friends and fellow graduates serving part-time NS also made them more miserable. This developed in them a strong distaste to serve NS and to continue their career with MID after their ROD (run out date as used then).

During the later part of officer cadet training, a small number of graduate cadets took up the offer to be converted to SSC officers and were sent to Israel for training on technical support of armoured vehicles. The numbers were however quite small and was done almost three-quarters of the way through the training cycle, and also during a time when the graduate NS trainees had a poor perception of the Army. However, these cases were exceptions rather than the norm for the progression of NS graduates.

The negative vibe on this unfair treatment accentuated into the "Why me?" emotion that graduate NS officers sought to obtain a clarification from the then Permanent Secretary of Defence Ministry but the issue was never satisfactorily addressed. This would continue well into the time when graduates eventually became commissioned officers receiving a higher allowance of around \$500 per month.

Two other events also had bearing on the perception of graduate NS officers on the organisation. Due to the rapid build-up of the SAF, the graduate civil servants were initially drafted to serve three months of NS and on their completion of basic training, they were told that their NS service was extended to two years. Furthermore, nearing the completion of the two-year NS, the service for NS graduate officers was extended to three years. Although the frequent changes in the policy were understandable given the changing requirements caused by the accelerated withdrawal of the British forces, in the NS graduate officers' perspective then, this was the extension of unfair treatment that set their long-term career plans back by three years, while their contemporaries outside were making further progress.

Within the context of unhappiness surrounding NS then, the development of the Technical Department in its early years was an uphill battle. The first major challenge was to build up the strengths of the Technical Department as the tight supply of good graduates and poor retention of experienced personnel were big issues. Secondly, given the strong distaste of graduate NS officers on the Army, the motivation and cohesion factors were of significant concern.

However, to the group of NS officers who were posted to the Technical Department headed by CPT Lui Pao Chuen, it was a refreshing change from life in SAFTI. In a relatively short period of time, the distrust of the Army

and the willingness to step forward to serve replaced the previous misunderstandings and negativity. The energy and morale improved, as the officers felt that their work was appreciated and they were learning new things.

Despite the changed environment, the graduate officers within the department were still handicapped on two fronts. Firstly, there were limited experienced persons to provide guidance, and when in doubt, there was no one to turn to for consultation. Secondly, interactions with the logistics bases were often difficult as personnel from the bases viewed themselves as superior in expertise to the fresh new hands inducted to the Technical Department. There was insufficient cooperation and cohesion between the two groups to work things out together and new officers had to navigate this complex work environment to develop healthy relationships.

From the first batch of NS graduate officers, 2LT Ho Tat Hung, 2LT Lee Huang Shang, 2LT Lim Thye Soon and 2LT Sng Bock Thiam were quickly inducted to work alongside SSC officer LTA Seow Tiang Keng to build up the Technical Department under the leadership of CPT Lui Pao Chuen. Three sections under the umbrella of General Supplies, Ordnance and Vehicle were set up. The early activities included preparation of technical specifications for procurement, exploring and developing simple prototypes such as general purpose machine gun (GPMG) mounting on a Land Rover vehicle, and conducting test and acceptance of prototypes and initial products before handing them over to the TEA section of the Logistics Division for ongoing operations.

In the following six months, there was rapid expansion of the set-up, with NSFs 2LT Sia Chong Hean, 2LT Lee Soon Khiong, 2LT Chan Yok Han, 2LT Lee Teng Kiat, 2LT Tan Suan Yong and 2LT Wan Siew Kay joining the department. More sections were set up including a General Administration Section,

Ammunition Section, as well as Civil Engineering Group. A few key activities necessitated this rapid expansion, namely the decision to acquire V-200 vehicles, the expansion of CIS beyond just AR-15 manufacturing to also include making of mortar bombs and the rapid build-up of army bases.

While all these activities were progressing, a number of NS graduate officers were required to travel overseas to carry out their jobs, including prototype-testing of weapon systems on V-200 at the manufacturing site and reviewing specifications of vehicles. Others were asked to look into the bases to see whether improvements to maintenance and repair services could be made. There were also instances of the malfunctioning of ammunition that were put into the hands of the Technical Department to assist in the investigation. These varied activities, while they may look simple and out of the scope of modern defence science and technology organisations, had provided the learning experiences and motivation for the NS graduate officers to regain the energy level and to fill the gaps created by the rapid expansion of the SAF.

Beyond serving NS in the Technical Department, it was regretful that many NS graduate officers in the early years did not remain to serve in the Army as regular officers. One exception, however, was Mr Cheng Fook Choon who went on to become CEO of ODE, but passed on young while on the job. Regardless, many of us who had served under CPT, and later MAJ Lui Pao Chuen were profoundly grateful. The experience with venturing into areas that we were not trained in, the "never say die" attitude in approaching challenges whether technical or human-related, and the energy to keep working while the workload was piling up, had become guiding work ethics that propelled us to be successful in our respective careers outside the SAF.

Creation of Ministry of Defence and Ministry of Home Affairs

The Ministry of Defence (MINDEF) and the Ministry of Home Affairs (MHA) were created on 11th August 1970 with the splitting of MID. MHA remained at Pearl's Hill until August 1977 when it moved into the camp of the HQ Far East Land Forces at Phoenix Park, Tanglin Road. In 1972 MINDEF moved out of Pearl's Hill to the UK HQ Far East Land Forces Camp at Tanglin.

Dr Goh Keng Swee was appointed the first Minister for Defence on 11th August 1970.

A top priority for Dr Goh Keng Swee was the development of Air Staff and Singapore Air Defence Command (SADC). He had a choice between continuing the build-up with SAF Army officers or to employ RAF officers. Dr Goh chose the latter.

There was a major change in the management style of MINDEF. Dr Goh Keng Swee built organisations around individuals and not individuals to fill the posts in an organisation structure. Layers of decision-making committees were eliminated with the decentralisation.

Project directors were appointed for every single major project. They were given authority to conceptualise, plan and implement projects. A 2nd Permanent Secretary (2PS) was appointed with Mr JYM Pillay being the first 2PS of MINDEF. He established the Science and Management Group (SMG) to assist him in the conceptualisation, planning and management of major projects like the handing over of Bloodhound surface-to-air missile system from the UK to Singapore.

Mr Pillay was head of SMG with MAJ Lui Pao Chuen as his deputy. The Public Service Commission provided SMG with a list of their top scholars who were serving in various ministries for selection to become

systems engineers in SMG. Mr Lim Siong Guan who was serving in PWD joined SMG and his first project was the introduction of 35mm anti-aircraft guns into the SAF. The conceptualisation, planning and project management of Junior Flying Club was his second project. A major preoccupation of SMG was in the development of the Air Force, and the technical infrastructure for the support of a technologically-advanced military.

On 18th March 1975, the Straits Times reported a question raised in Parliament by MP JF Conceicao and MP Ng Yeow Chong on the need for MINDEF to establish SMG to coordinate the introduction of various weapons. Dr Goh Keng Swee, the Minister for Defence said, *"Modern weapons are of a highly complex nature, requiring intricate programming, logistics and manpower, and are also closely related. It is therefore necessary to ensure that there is minimum waste. Weapons like Bloodhound missiles cost \$100 million, when operational, would require a wide variety of skills for maintenance and servicing. It would be the responsibility of the Science and Management Group to co-ordinate the programmes. The group consisted of engineers sent abroad for training, and they had distinguished academic records in mechanical, civil, electrical and other fields."*

Sustaining the Development of Defence Engineering Capability

There was, however, a storm gathering. All the engineers from the first batch of NS graduate officers left on completion of their three years of obligatory service (this was later reduced to 2.5 years for officers and NCOs; all graduates who were not commissioned as officers were appointed as NCOs during their NS). They could not be persuaded to sign up as regular officers or on SSC. They felt that they had lost out to their peers who were selected for part-time NS, and therefore wanted to pursue their careers without further delay.

It became obvious that filling the establishment with engineers that were only serving

2.5 years of NS would not build up the engineering capability needed in our technical organisations. It was assessed that a minimum time of stay of five years would be needed for the accumulation of knowledge in a sustainable way.

When 2PS was alerted to this problem, he tasked that a board of senior engineers be formed to interview all enlistees for NS who had a degree in engineering or science to assess their interest in signing up for service in MID. The board found that a significant number of graduates would be willing to sign up for five years of service and be paid the market rate of \$900 per month upon commissioning as officers. This scheme of service was named the "Specific Term of Engagement" and attracted many top quality engineering graduates to sign up. An example is Mr Liew Mun Leong was the first civil engineer recruited under this scheme. Mr Alan Chan Heng Loon, a graduate in aviation from France, joined the SADC and Mr Alan Bragassam, a naval architect, joined the Maritime Command (MC).

The logistics and engineering units of the SADC, MC and Logistics Division were soon strengthened with the injection of officers who had degrees in engineering or science.

SAF Postgraduate Fellowship Programme

The SAF Postgraduate Fellowship programme to overseas universities began in 1971 at the same time as the SAF Overseas Scholarship programme. Between 1971 and 1973, four officers, MAJ Lui Pao Chuen, MAJ Henry Cheong, CPT Lee Kheng Nam and CPT Lim Lay Geok were sent to the US Naval Postgraduate School in Monterey, California for MSc degree in OR and System Analysis. CPT Quek Poh Huat was also sent to the same school, for MSc degree in Defence Management.

Sending Defence Engineers to Defence Industry and Other Ministries

As most of the work was not engineering in nature but more with the setting up of units and the associated administration and maintenance, there was a distinct dissatisfaction among the young engineers. This dissatisfaction came to a head in 1973 when a number of engineers wrote a petition to Dr Goh Keng Swee. 2PS Pillay met the engineers to hear their grievances. He identified the root of the problem to be a lack of engineering work and engineering leaders, and proposed that the engineers be sent from MINDEF to other ministries and the defence industries.

Only the SADC disagreed and made their case why the Air Force needed engineers. Dr Goh Keng Swee accepted their argument and allowed the Air Force to keep their engineers. The Technical Department, SMG and some smaller logistics and engineering units were closed and all the engineers posted out.

Mr Lim Siong Guan was posted to Singapore Automotive Engineering (SAE) and became the General Manager of the company within a year. The number of engineers in MINDEF had grown from 70 in 1971 to 200 in 1973, but fell back to 100 after the posting exercise. The Specific Term of Engagement scheme was scrapped. The closure of the technical organisations had an unintended consequence. The knowledge of the organisations and their files were lost.

Mr Philip Yeo, Head Organisation and Control Department, had the complete support of Director Logistics, Mr Ong Kah Kok to introduce computers and modern management systems to logistics organisations. He also led the development of field logistics for the Army and the training of logistics officers in the School of Logistics Administration.

With a mandate from Dr Goh Keng Swee, Mr Philip Yeo and his systems engineers led major changes in other MINDEF organisations. The Systems & Computer Division grew from being the Systems & Research Branch under the Organisation and Control Department in 1970 to a full division within a short time.

The rebuilding of engineering in the Logistics Division began in 1974 with Mr Lim Siong Guan moving back from SAE to MINDEF to be the head of the newly formed Ordnance Department. He became Director Logistics in 1975 and was succeeded by Mr Philip Yeo in 1976.

Guiding Principles for Procurement of Stores and Equipment

As our soldiers were small in size, one key operational requirement was for our equipment to be lightweight. They had to be as light as possible to ease the load that our soldiers would have to carry. The word “lightweight” was the mantra used in the evaluation of every piece of equipment and weapon for the SAF. The combat weight that a soldier would be allowed to carry in operations was such an important operational planning parameter that it had been approved by the PS(MID) Mr George Bogaars after much deliberation by the General Staff Division. The standard poncho available in the stores catered to the needs of British Army soldiers and was made from rubber. It was completely waterproof but heavy. Lightweight nylon ponchos that weighed less than half of the rubber ponchos were purchased instead.

Logistics Division also had to ensure the equipment purchased were good value for money. The helmet was a critical item for the protection of our soldiers. Samples of different types of helmets were evaluated. A helmet made of titanium was very light and strong but the price was very high. The US Army M1 helmet weighing 2.85 pounds was finally selected as standard helmet for the SAF. We

did not buy the best lightweight titanium helmet because it was not found to be good value for money.

US Military Standards were used as reference for the specifications of combat control equipment and ammunition. Safety was the topmost factor in the specification of weapons and ammunition. As the logistics staff had no experience in the development, production and use of weapons and ammunition, they had to be extremely diligent to learn all they could from publications and experts from overseas. Industrial standards were adopted as the specifications for equipment that would not be deployed in and subject to the harsh conditions in the field.

Myth of SAF Buying Second-Hand Equipment

There was a myth in the SAF that Singapore was so poor then that we could only afford to buy second-hand equipment, for example, dented steel US Army M1 helmets. It is true that the SAF was not wealthy in the fledgling years of Singapore’s independence but from the weapons that we had purchased, it is clear they were the best weapons of each class to meet the needs of the SAF. However, in view of the rapid build-up of the SAF in the early years, 1 and 2 SIR and Peoples’ Defence Force (PDF) units continued to use the equipment that they were using as newly-formed units like 3 SIR, 4 SIR and 20 Singapore Artillery (SA) and schools at SAFTI had priority for equipping.

Professional Managers Employed for Procurement

Senior logistics management staff were recruited from the private sector on Short Service Commissions. A critical appointment was the Head of PP&P (Plans, Provisioning & Procurement) Department. This appointment was filled by MAJ Siew Nim Wah, a very experienced senior executive with extensive

knowledge and experience on the management of procurement. He was supported by a younger business executive, MAJ Yeo Teck Meng, a graduate in Economics who was employed by a large corporation. MAJ April Wee who had served in logistics and administration in 1 SIR provided the department with expertise on military needs.

An Administrative Officer, Mr Foo Kok Swee, a PSC scholar who graduated in the US in 1964 with a degree in electrical engineering, was made the Head of Organisation and Control Department of the Logistics Division.

Professional engineers were also recruited on Short Service Commission as lieutenants or captains on enlistment. They would wear SAF uniforms for work in the Logistics Division, Logistics Bases and Communications and Electronics units. A freshly-graduated mechanical engineer, LTA Chiang Woon Seng and an electrical engineer, LTA Lee Teck Hoe were recruited as Short Service Commission officers for the PP&P Department. The Test and Evaluation Section was established in November 1966 with the recruitment of LTA Seow Tiang Keng (electrical engineer), LTA Chye Wee Seng (chemistry graduate) and CPT Lui Pao Chuen (physics graduate).

Armament Officers

The expert on weapons then was MAJ Peter Law. He was an officer from 1 SIR with a great passion for all types of weapons. He read up everything that he could find on weapons and ammunition and became an authority in the SAF on armaments. He was a principal officer in the selection of weapons for the SAF and held the appointment of CO of WAOB located at Mount Vernon Police Camp.

Ammunition officers of the SAF would need to have the best professional training on the subject and be qualified. The UK provided assistance in the build-up of expertise by accepting three officers for a year’s training

as ammunition specialists. They graduated in 1968 and returned to take up leadership and training appointments in the SAF. While they were on course in the UK, a British Army armament and bomb disposal expert Warrant Officer Clifton Webb was the licensing officer of the SAF.

Upon return, the most senior officer MAJ Wong Geok Seam became CO of WAOB. CPT Seow Whatt Choon assisted him with training of ammunition technicians. The UK’s regulations on the management of explosives were adopted by the SAF. The knowledge that they had acquired in the UK was developed into lesson “formats” for training.

Selection of Weapons

The most important piece of equipment for a soldier is his personal weapon. The most important decision for the SAF was the selection of this personal weapon and the calibre of its ammunition. The Self-Loading Rifle then in service with the SAF in 1965 was very reliable but heavy. The 7.62x51mm ammunition was standard North Atlantic Treaty Organisation (NATO) ammunition.

The rifle for the SAF had to meet the requirement of being lightweight for easy carriage and performance such as in the areas of accuracy, penetrating power and reliability. The weight of the ammunition was a critical factor in the selection.

All the rifles under production then were considered. The German Heckler & Koch G3 rifle of the German Army was found to be very well-designed. The Russian AK-47 designed by Mikhail Kalashnikov was a great assault rifle and was widely used by militaries in the East. The rifle was also in production in many countries. Almost 100 million AK-47s were then reported to be in service. The 7.62x39mm round of the AK-47 could be fired from standard NATO 7.62x51mm weapons. With a battle-proven track record the AK-47

was a very attractive rifle for the SAF. But it was heavy, at 5kg with a loaded 30-round magazine.

AR-15 Rifle

The competitor to AK-47 was the AR-15 which was then not in production for military customers. Two designers of AR-15, Eugene Stoner and Jim Sullivan, had a reputation in the armament world of being great weapon designers. The AR-15 was light in weight, accurate and could be fired in automatic mode with a high rate of fire. Colt Industries bought the rights for this rifle from the small company, Armalite, and began marketing the rifle to the US Army, Marine Corps, Navy and Air Force, and other militaries worldwide. Small numbers of AR-15 were purchased by the US Army and US Marine Corps for test and evaluation, and operational trials.

Lightweight was achieved with the use of aluminium for the receiver and plastic for the butt and other parts of the rifle. The only weapon parts made of steel were the barrel and the bolt carrier assembly. The weight of AR-15, without the magazine, was 2.9kg. The magazine was made from aluminium as compared to steel in the AK-47. But the greatest weight saving was achieved with a smaller calibre bullet, 5.56mm as compared to the 7.62mm standard round of the US Army and NATO. The 5.56mm round was half the weight of the 7.62mm round. For the same weight, a soldier would have twice the number of 5.56mm rounds. The barrel and firing mechanisms could also be lighter with the smaller 5.56mm round. The trade-off to achieve weight-saving was the lower penetration power. This was, however, not a serious problem for our infantry as their contact range was short.

The decision taken by the SAF in 1966 to adopt the AR-15 was a major one. Instead of selecting a proven rifle like the AK-47 or the Heckler & Koch G3, the SAF trusted its

assessment that the AR-15 would be more suitable to meet its operational requirements and become a future weapon of armed forces. The leaders of the SAF had the guts to move before the US Army had adopted the AR-15.

Their judgement was vindicated when the AR-15 was adopted by the US Army in 1969, and designated as M-16 to replace the M-14 as their standard rifle. Following the adoption of M-16, the US Army wanted all their soldiers in Vietnam to be armed with the M-16 in the shortest time possible. Had the SAF waited, they would not have been able to purchase the M-16 until much later as the production capacity of M-16 in the US was limited and the US Army had priority. An important lesson learnt from the selection of AR-15 was the great value in daring to be a leader instead of playing safe as a follower.

After much negotiation with the US, a licence was granted to Singapore for the production of M-16 by CIS. The production of M-16 was much faster than the recruitment of soldiers into the SAF and there was a stock of M-16s to meet all the needs of new units being raised.

The knowledge that Singapore had equipped all its units with M-16s became a political issue in the US. There were accusations in Congress that their soldiers in Vietnam were deprived of M-16s because of commercial interests in the sale to Singapore.

M-16 had teething problems in Vietnam. The bolt of some rifles could not close if the weapon was dirty and not properly cleaned after firing. This would result in stoppages. The problem was solved with the adoption of a “forward assist” button to push the bolt into the lock position with the thumb. There was no more need to unlock the receiver to clear the stoppage.

Though M-16 had been replaced by SAR-21 in 1999 as standard rifle of the SAF, 5.56mm calibre has remained the SAF standard till today.

General Purpose Machine Gun

The best GPMG in the Western World was the Belgian FN MAG. It was designed by Ernest Vervier of Fabrique Nationale. It had been in operational service since 1958 and battle-proven. The Bren gun, a .303” calibre Light Machine Gun in service with the SAF then was completely outclassed. But the weight of GPMG at 11.8kg was heavy. It would be used to provide direct support fire from firebases in an assault of an objective.

As the patent of GPMG MAG would expire in late 1970s, a local development of the weapon for production was undertaken by Ordnance Development and Engineering of Singapore (ODE, now ST Kinetics). The prototype GPMG was completed in 1974 but it took a few years to make improvements on parts’ interchangeability and reliability.

81mm Mortar

The evaluation of the 81mm mortars for the infantry resulted in the 81mm mortar manufactured by SOLTAM to be the clear winner. The mortar was both lightweight and accurate. Although there were some quality problems, they were eventually sorted out by the company and the infantry was satisfied.

Licensed production of the 81mm bombs began in CIS with the manufacture of the body parts in the plant at Jalan Boon Lay, and the filling of TNT charge in the new plant at Bukit Timah. Production of the 81mm mortars was subsequently done by ODE.

Engineers from the Logistics Division played an important role in testing and evaluation of the CIS mortar bombs, and accepting them after tests for use in the SAF.

60mm Mortar

The SAF had a requirement for indirect fire support at the company level. The 81mm

mortars at the battalion level would not be as responsive to the needs of the infantry in assault and in defence. The M2 mortar was used by the US Army as a light infantry support weapon in Vietnam. The weight of the mortar was 19kg and the bombs weighed 1.4kg. SOLTAM had a lightweight mortar which weighed less than 8kg with a range of 1.6km, comparable to that of the M2 mortar. The SAF selected the SOLTAM lightweight 60mm mortar on completion of the test and evaluation programme.

There were teething quality problems when the mortar entered service but were eventually rectified.

120mm Lightweight Mortar

The SAF selected the 120mm lightweight mortar as its Artillery weapon. Though the range of the 120mm mortar was short at 6km compared to that of the US Army’s M2A1 105mm howitzer’s range of 11km, it had a very large warhead and high rate of fire.

The deciding factor in favour of the 120mm lightweight mortar was the element of surprise. Attack by artillery with this weapon could come from position unexpected by the enemy. The concept of operation was for the 120mm mortar and ammunition to be man-packed and carried by the crew to the deployment site. The three components of the mortar, barrel, base plate and tripod, would be man-packed.

At a demonstration at the SAFTI Live Firing Area a battalion of 120mm mortars was deployed right in front of the spectator stand under camouflage. The spectators were shocked when the mortars opened fire and revealed their position.

Despite the fact that the soldiers assigned to Artillery must meet stringent physical standards, the carriage of this heavy load in long marches had caused injuries.

There was also an operational problem. The lightweight base plate would sink into the ground after firing a few rounds. Different solutions to reduce the sinking like adding a ring around the baseplate to increase its surface area were found to be operationally unacceptable.

After all the attempts to solve the base plate sinking problem failed, the decision was to replace the lightweight base plate and use the standard 120mm mortar base plate instead. To minimise injuries, deployment by foot was also changed to the 120mm mortars being towed by Land Rovers or Unimog trucks.

This was one case when the concept of operation could not be achieved because of technical limitations of the weapon system. Rosemary Yeo and her fellow writers will continue the stories in the development of artillery for the SAF in Chapter 3.

Anti-Tank Weapon

M-72 Light Anti-Tank Weapon *versus* M203 40mm Grenade Launcher

The M-72 light anti-tank weapon (LAW) was a new lightweight anti-tank weapon adopted by the US Army in early 1963. It was used by infantry soldiers at the section level to defend themselves against tanks. It was simple to use and did not require a dedicated crew. It was cheap and the launching tube would be thrown away after the round had been fired. The High Explosive Anti-Tank (HEAT) warhead was 66mm calibre and could penetrate 200mm of Rolled Armour Steel, the reference thickness for anti-tank weapons to defeat the front armour of main battle tanks (MBTs). It was also specified to penetrate 600mm of reinforced concrete. The limitation of the M-72 was its short range of about 150m. The back blast of the M-72 was also very high, and the launch position would be exposed when a round was fired.

If the round did not hit the target, the firer would be in danger from counter-fire by the tank or armoured fighting vehicle.

While the M-72 appeared to be an obvious choice for use as a secondary anti-tank weapon of our infantry section, it was still an additional weapon to be carried.

The M203 40mm grenade launcher, weighing 1.4kg and fitted to the bottom of our AR-15 rifles, would reduce the combat load of the soldier. Besides the advantage of being lighter, the launching of the grenade did not have a large launch signature. There was no back blast. The weapon operator would not need to have his rear clear of his buddies when firing the grenade launcher. He could also fire 5.56mm rounds and 40mm grenades without having to change weapons. The different 40mm ammunition, from illumination round to buckshot round, made it a very versatile weapon for the soldier.

The major disadvantage of the M203 was its low armour-penetrating power. The High Explosive Dual Purpose round (HEDP) could only penetrate 50mm of armour. It could defeat APCs but not tanks. This weapon was new and introduced into the US Army only in 1969. It was finally selected for the SAF. The selection of the 40mm grenade was a decision that led to the later development of a family of 40mm weapons and ammunition that are still in service with the SAF today.

M20 *versus* Carl Gustav Anti-Tank Weapon

The decision for the primary anti-tank weapon for the infantry was more difficult. The two finalists were the M20 from the US and the 84mm Carl Gustav from Sweden.

The M20 US Army Bazooka, a man-portable anti-tank rocket weighing 6.5kg, was considered by the SAF for adoption as the infantry's anti-tank weapon. The range of the M20 was 300m against stationary targets.

The competitor was the Carl Gustav M2 84mm anti-tank rocket which had more than twice the range of M20 and weighed 4kg.

The Carl Gustav used a rifled barrel to spin stabilise its rounds as compared to the use of fins to stabilise the M20 round. Spin stabilisation had the advantage of greater accuracy. The penalty for spin stabilisation was the need for a heavy steel rifled barrel. The weight of the Carl Gustav launcher at 16kg was much heavier than the M20 at 6.5kg. But it could hit and destroy stationary targets at 700m and tanks at 150m.

It was a difficult choice. Despite a concern that soldiers could discard the weapon during long marches when tired, the SAF selected the Carl Gustav.

The highly desired lightweight requirement was given up for the capability to engage targets at 700m.

106mm Recoilless Rifle

The US Army's M40 106mm recoilless rifle was the obvious choice for this class of weapons. It saw action in the Vietnam War and had a reputation for operational effectiveness and reliability. A disadvantage of the 106mm recoilless rifle was the large back blast. Despite wearing ear protectors some soldiers did suffer various degrees of hearing loss from repeated exposure during live firing exercises.

The weapon was mounted on a M151 jeep. Instead of modifying the Land Rover which was standard in the SAF, the decision was made to purchase it with the jeep. This violated the concept of commonality of combat vehicles to ease logistics support in the field.

The M151 jeep had been modified for carriage of M40. The training for drivers of the M151 jeep had to include the weapon on-board as its centre of gravity was higher. A dummy M40

was made with a pipe and barrel filled with concrete to simulate the weight distribution of the weapon during such trainings. Jeeps running on public roads in the western parts of Singapore became a common sight.

20mm Cannon

The last weapon the SAF needed for infantry support was the 20mm cannon to engage targets protected by the steel armour of armoured personnel carriers or reinforced concrete walls of bunkers. There were two finalists, the Swiss Oerlikon GK 204 and the French Hispano Suiza Hs.404. On completion of the evaluation, the SAF decided that with the 106mm recoilless rifle and the Carl Gustav, the operational need for this weapon had diminished.

With this decision, the test and evaluation programme for the SAF's infantry weapons was complete.

Anti-Personnel and Anti-Tank Mines

The SAF had a need for anti-personnel (AP) mines and anti-tank (AT) mines to deny enemy freedom of movement in selected areas of operation.

With the established TNT plant of CIS and previous experience gained in the manufacturing of mortar bombs, the local manufacture of mines would be relatively simple.

During the evaluation of AP mines, a request for information was sent to different suppliers. One of the suppliers, Brennan Co, was the agent for some European companies and had catalogues of AP mines then under production in their principal's plant. The manager obtained a training mine from PRB, Belgium and sent it to the TEA Section for evaluation.

The marking on the AP mine was "training mine". A TEA officer dismantled the mine to study the trigger mechanism. Suddenly, there

was a flash and bang with white smoke pouring from the body of the mine. He suffered burns on his hand and was rushed to the medical centre for attention. The mine was a training mine with a trigger and a smoke charge to let trainees and instructors know that the mine was activated. A new rule was added to the TEA procedure: No training items on explosives would be allowed into the office. Armament experts in the WAOB must first check and certify them to be harmless before they could be examined by TEA engineers.

The SAF adopted the 7kg AT mine made by Alsetex Astrale to be used against MBTs and the 3.5kg mine to immobilise pursuing vehicles. The PRB non-detectable AP mine was selected. The Claymore mine used by the US Army was selected for ambushes and perimeter defence.

Local Production of Stores and Equipment

A major task given to the Logistics Division by Dr Goh Keng Swee was to nurture the local industry to produce equipment needed by the SAF. General equipment like uniforms, boots, webbing, ponchos and accommodation stores were made in Singapore. Companies like Diaward had projected the needs of the SAF for webbing and set up a production plant in Singapore to capture this emerging market.

Food for Our Soldiers

Quality control of rations proved to be a challenge as delivery was made directly to the cookhouses of SAF camps every day. Some dishonest contractor staff would try to bribe the cooks and quartermasters of units to accept lower quality of fresh rations that they were delivering.

TEA Section staff quickly discovered that soldiers ate food and not calories or nutrition. If the food was not palatable they would not eat it. The challenge was to serve food that

was palatable. The key to the feeding problem was good cooks. The challenge for the SAF was finding good cooks to train 18-year-old NSF soldiers to become cooks in the Army School of Catering.

Food for our soldiers was very important. A dietician, LTA Lee Pui Chin, newly graduated from an Australian university was recruited into TEA Section. She had to prescribe the nutritional value of the rations that were being purchased for SAF units. She was also responsible for checking on the quality of fresh rations supplied by contractors to the SAF units.

Besides fresh rations, the SAF required “compo rations” that soldiers carried in their back packs during training exercises and for operations. Each compo ration pack contained all the food that a team of two soldiers would need for 24 hours. Hexamine solid fuel tablets were provided in the pack for food warming and boiling of water for coffee and tea.

However, in some operational scenarios, the lighting of fire to cook food was not allowed. The compo rations had to contain sufficient food that could be eaten directly from the pack. A soldier in the field was assessed to need a calorie content of 4,000 calories then.

Operational readiness required the compo rations to be stocked at the units and issued when required. As the compo rations was expensive compared to fresh rations, the shelf-life of all the items had to be for as long as it was possible. The plastic water-proof package could not be resealed by units to replace items that had exceeded their shelf-lives. All the food thus would have to be consumed before the expiry date of the item with the shortest shelf-life. This was not popular with the soldiers as they would be eating compo rations instead of a freshly cooked meal.

Canned chicken was an obvious choice for the protein of the compo rations. Hard “dog

biscuits” that would not be crushed by rough handling were also included but they were difficult to eat.

The need that could not be met by our food industry was the production of instant rice that did not require the lighting of fire for cooking. The Thai Army had instant rice in their compo rations pack that could be eaten after adding water. Our two food industries, Yeo Hiap Seng and Amoy Canning, tried their best but could not replicate the Thai instant rice.

The work on food was never done as tastes would change with time and technology would also provide new options that were not feasible earlier. The staff of TEA Section became test subjects when new food items were being evaluated for the compo rations pack.

There was nothing like cooked food in the field to raise the morale of troops. But cooking in the field was quite different from cooking in the cook house as equipment would need to be smaller to be brought into the field. The development of the SAF field kitchen thus began in mid-1969, together with the development of the doctrine on field logistics.

The problem of contractors creating temptation for our quartermasters and cooks was finally resolved with the setting up of Singapore Food Industries (SFI) to supply food to the SAF. The centralisation of quality assurance ensured that fresh rations would be of uniform quality across all SAF units. In the initial years SFI tried their best to import frozen meat and fish from sources that offered the best price. Frozen fish imported from Russia was found to be inedible by our soldiers and the entire stock of frozen fish was rejected by inspectors from the Logistics Division.

But the problem of finding enough cooks to prepare palatable food remained. There was not enough time to train NSFs into good cooks before they completed their service. However,

the outsourcing of cooking to commercial companies had improved the palatability of cooked food in the SAF cook houses.

Local Production of Ammunition

In 1966, Dr Goh Keng Swee concluded that for strategic and economic considerations, Singapore would need to build an armament industry for Singapore. He was neither deterred by the technical challenges nor the high cost of setting up an armament industry. CIS was established in 1966 with its first project, the production of 5.56mm ammunition for the Colt AR-15 that had just been selected to be the standard rifle of the SAF. A young administrative assistant (then still on probation), Mr Tham Mow Siang from People's Association was posted to MID in March 1966 and given the responsibility to set up CIS.



Chartered Industries of Singapore at 249 Jalan Boon Lay, circa 1968

DEVELOPMENT OF ARMAMENT

From the 1967 to the 1990s, when Singapore's citizen soldiers were enlisted for NS or mobilised by the SAF, each soldier was issued a Singapore-made M-16S1¹ (early batches used the AR-15, predecessor to the M-16) assault rifle that fired 5.56mm bullets.

Today, when Singapore's citizen soldiers are enlisted or mobilised by the SAF, each soldier is armed with a Singapore-made SAR-21 5.56mm assault rifle – a Singapore Assault Rifle for the 21st century, specially designed and built for the men and women who serve the SAF.

On paper, it may seem that the 5.56mm assault rifle that Singaporean soldiers now carry into operations delivers the same firepower as the M-16S1 rifle used by the SAF before the SAR-21 was introduced in 1999.

Innovations in Defence

If you look beyond the obvious, however, you will find telling signs of the contributions Singapore's defence scientists and engineers have made to the SAF's mission readiness and deterrent edge. The SAR-21's technical and operational advantages over the M-16S1 are numerous.

With the M-16S1, an infantry battalion required about half a day to prepare itself for operations. Much of the time was spent on the time-consuming process of zeroing the rifle using a modified ice pick, Canadian Bull Target and test shots at the firing range to painstakingly adjusting the iron sights on M-16S1 rifles by hand to suit each soldier.

¹ M-16S1 is the version of M-16 that CIS had purchased the licence to produce.

It is a tedious process that planners from MINDEF and the SAF, working alongside weapon designers from the defence industry, resolved to streamline: Every minute counts when the SAF is needed to confront clear and present dangers that threaten Singaporeans.

The SAR-21's factory zeroed 1.5x magnification integrated aiming scope allows every soldier to achieve good accuracy for a high hit probability without the need for individual zeroing in the field. The SAR-21 also has a laser aiming device built into the hand guard for easy target acquisition during the day and night in close combat operations. With the SAR-21, an infantry battalion can be fully armed and ready for deployment in a much shorter time. NSmen making the transition from citizens to soldiers as their mobilised unit moves from a peacetime posture to operations need only draw arms and ammunition, then proceed to the firing range fully confident that their rifles will place every shot where they are aimed.



SAF soldier with the SAR-21 assault rifle

Indeed, the SAF records show that more than 6 out of 10 NSmen are marksmen – notably better than battalions armed with the M-16S1. Such accuracy will prove invaluable during a firefight.

Weapons that allow the SAF to respond more speedily and sustain the delivery of lethal force contribute to military deterrence. By showcasing the SAR-21's operational

advantages, aggressors will recognise that the SAF's full-force potential can be achieved in a much shorter mobilisation cycle, and the accuracy of automatic rifle fire will take its toll on enemy combatants.

The journey of the development, production and deployment of a weapon system is long and tortuous, fraught with danger of cancellation of the project at every milestone. The successful deployment of the SAR-21 is an example of this journey. With the introduction of the Ultimax 100 light machine gun into service in 1982, the firepower of an infantry section was significantly increased. The optimal size of an infantry section and weapons was determined through operational trials with one battalion of troops. The seven-man section was finally selected by the Army after much debate and operational trials. The next question that was addressed was the operational requirements of the new assault rifle that would be significantly more effective than the M-16S1. The new assault rifle must be designed to meet the needs of Singaporean soldiers who were smaller in build than their counterparts in the US Army. Many of them were short-sighted and aiming of rifles during wet weather could be problematic.

Assault rifles would need to engage target at different ranges. Fighting at close quarters was very demanding as there would not be time for careful aiming. It would take a soldier lots of training to be able to point and shoot well. Speed of engagement was critical as the enemy could be expected to shoot back. A laser pointer would be invaluable for the soldier as he would be able to point and shoot without looking through the sight of his rifle. This led to the operational requirement for a built-in LAD (Laser Aiming Device).

For longer-range engagements, the ability to align the barrel of the rifle along the target line, with the target moving, was a critical requirement. An assault rifle with iron sights would require the soldier to look through

the hole in the rear sight and align the front aiming post with a target. Acquiring a moving target in one's gunsight would be a demanding skill to learn and difficult to maintain. The time from detecting a target to squeezing the trigger was a critical performance parameter that would differentiate the new assault rifle from the M-16S1.

Fitting a telescope on the M-16 could partially improve the performance but it would not be as robust a solution as a scope that was designed integral to the weapon. The built-in aiming scope with a 1.5x magnification was optimised for target acquisition and not for long-range target engagement.

A sharpshooter providing long-range support would find the 1.5x magnification inadequate and would need to use a 3.0x magnification. For the latter, there is a SAR-21 marksman variant with 3.0x magnification aiming scope.

All the other shortcomings of the M-16S1 were taken into consideration in the development of the SAR-21, leveraging advances in technology to deliver marked improvements in accuracy, ergonomics and ease of use.

A similar observation is derived when analysing the Army's indirect fire weapons. The calibres of mortars deployed have stayed consistent, with 81mm and 120mm tubes used since the 1970s. On paper, the Army's mortar teams pack the same punch as yesteryear. Indeed, one could argue that the retirement of Soltam 160mm Very Heavy Mortars from the Singapore Artillery's ORBAT had resulted in a capability gap in mortar bomb throw weight that today's Army lacks. The reality is, however, quite different.

While the sizes of mortar tubes have stayed constant, product improvement projects led by the defence industry's Large Calibre Ammunition teams have given the Singapore Army's 81mm and 120mm mortars an expanded range ring and a more lethal kill

zone at point of impact. Fuses designed and made in Singapore, optimised for use in terrain where targets may be masked by foliage cover, give mortar teams the flexibility to deliver airburst barrages which are lethal against dug-in targets masked by terrain. Some of these fuses are touted to be “easier to set than an alarm clock”. These enhanced target engagement capabilities, complemented by assets tasked with real-time target acquisition like UAVs, result in a sensor-to-shooter loop that is faster, more accurate and more resilient to enemy counter-fire. During a fire mission, mortar batteries deployed by the SAF are more effective as these mortars have a longer reach and capability to destroy a wider range of targets.

Furthermore, reassigning towed 120mm mortars to infantry battalions and streamlining tube artillery battalions to just 155mm heavy artillery guns (instead of a mix of 105mm and 155mm guns, and 120mm mortars previously) increases the firepower of the infantry while bringing attendant advantages in the management of ammunition supplies since all tube artillery battalions share the same projectiles and charges.

The SAF’s transformation into a third generation fighting force must therefore be seen with a wider aperture which takes into account advantages brought into play by individual weapons, as well as structural and organisational changes to its ORBAT. Such battle-winning advantages are not obvious with a cursory look at the weapons and ammunition that the Singapore Army uses.

50 Years of Small Arms and Ammunition Developments

This chapter will attempt to highlight some of the less obvious, yet impactful and invaluable contributions that Singapore’s weapons designers have made to the SAF in the past 50 years. This half-century milestone is significant for Singapore’s weapons and

ammunition project teams. The milestone’s significance stems from the fact that weapons engineering represents a specialised area of military technology that obsolesces quickly unless efforts are made to institutionalise lessons learned and experiences gained, and in nurturing successive generations of engineering staff to hold the torch.

Today, the SAF can count on the Singapore’s defence eco-system to design, develop, manufacture and maintain infantry weapons like automatic weapons, support weapons like anti-tank guided weapons and specialised ordnance for combat engineers like rocket-propelled LAMBE mine-clearing line charge.

The projects showcased in this chapter tell one part of their journey. Engineering prototypes ranging from 5.56mm flechette rounds, a multi-barrel 20mm gatling gun and fast-firing 9mm machine pistols never made it to the production stage. That said, the weapons engineers who worked on such projects had nonetheless gained invaluable first-hand experience in firearms and ammunition engineering.

Self-Reliance vs Self-Sufficiency

In the past 50 years, Singapore has invested heavily in efforts that give the SAF technological and operational advantages in battle. Central to this effort is the measure of self-reliance in defence materiel deemed essential for mission success.

Self-reliance is not the same as being self-sufficient. As a small city state with limited resources, we must recognise that we can never be self-sufficient in all defence requirements because doing so would divert needed resources away from other segments of our economy.

Singapore can, however, aspire to be self-reliant in areas of military technology deemed essential for the SAF’s mission success. This

means we will possess a minimum essential capability, which is a baseline level of defence engineering know-how needed to design, develop, manufacture and maintain key pieces of defence equipment and sensors.

Experience and expertise gained from indigenous defence projects reward the defence-ecosystem with the know-how and confidence to support MINDEF and the SAF’s survey of the landscape of current and emerging threats, and recommend solutions for countering these threats. Such know-how, paired with a rigorous and systematic process for weapons evaluations, contribute immeasurably to Singapore’s reputation for being a reference customer who makes astute weapons purchases.

Soon after Singapore’s independence, the ability to manufacture and support small arms was identified as one of the key areas of defence technology that the young Republic must master.

The assault rifle is the cornerstone of the SAF’s firepower. The rifle’s value counts for nought without a ready and reliable supply of rifle ammunition that fires reliably and consistently whenever the trigger is pulled.

The accuracy of this weapon, the effectiveness of its ammunition, operational effectiveness (Is it light enough for sustained operations? Can targets be acquired and shots delivered swiftly during a firefight? Can the magazine be changed quickly?), and reliability of the rifle and ammunition are central to the success of the SAF’s operations.

In the SAF (and indeed any conventional army), the assault rifle and rifle ammunition are stocked in greater quantities than any other implement of war. A fully mobilised SAF has more than 300,000 men and women under arms. Assault rifles are issued on the scale of hundreds of thousands. Singapore’s war reserve of bullets is stockpiled in the

millions. The sheer quantity of weapons and rifle ammunition issued explains why the reliability of our small arms and ammunition is paramount. A failure rate of a fraction of a percent, when magnified by the scale at which such arms are issued, could compromise the safety of the NSF, NSMan or Regular whose life depends on the serviceability of the weapon and effectiveness of its ammunition. A stoppage requiring immediate action - IA in army parlance - in the midst of a firefight, or dud ammunition, could possibly cost the life of an SAF warfighter.

This explained why Singapore’s defence planners, particularly our late founding Minister for Interior and Defence and later Minister for Defence Dr Goh Keng Swee, set very high standards for CIS (now known as ST Kinetics).

Recognition of the importance of the assault rifle as the backbone of the SAF’s firepower and an assured ammunition supply explains why the first CIS project had centred upon the manufacture of 5.56x45mm ammunition – which was then a new calibre being evaluated by NATO forces and the US Army.

Their journey began in 1966 on a humble footing.

Production of 5.56mm Ammunition

The local production of the 5.56mm ammunition was a very ambitious project. In 1966, Dr Goh met Sir Laurence Hartnett who was then the General Manager of the General Motor’s car producing factory in Australia. Dr Goh was impressed by his wide knowledge and ability to create innovative solutions for engineering problems. Dr Goh gave him the challenge to plan and develop CIS to be the forerunner to Singapore’s defence industry. The first project was the production of 5.56mm rounds for the AR-15 rifle made by Colt Industries, Connecticut that had just been selected by the General Staff Division

to be the standard rifle of the SAF.

CIS was set up in 1966 with an office in the Cathay Building while its future factory along Jalan Boon Lay was being built on a 69-acre site in the new Jurong industrial estate. The CIS factory was one of the first factories in Jurong. A young Administrative Officer, Mr Tham Mow Siang, was appointed the Project Director for the establishment of CIS, reporting to Director Logistics and to Dr Goh.

Mr Tham recalled how CIS was set up, “In 1966, Sir Hartnett, consultant to then MID for the manufacture of small arms ammunition, Mr Robert Lee Bee Kow, Precision Metal Machining Workshop Manager and I, posted to MID, were appointed by Dr Goh to look into the procurement of machinery for the manufacture of small arms ammunition. Mr Robert Lee was identified and appointed by Dr Goh to go on the mission with Sir Hartnett and me because of his comprehensive knowledge on machinery and precision machine tools which, in the mid 1960s, very few Singaporeans had.

In August 1966 the three of us visited several companies in Europe. After having seen their machinery and their capabilities, and studied their offers, we found that Manurhin, a company in Mulhouse, France, to have the most suitable machinery with full capability for the manufacture of small arms ammunition. We sent a telegraph to Dr Goh informing him of our findings and for his decision to proceed with the purchase.

We waited in London for Dr Goh’s reply so that we could return to Mulhouse to negotiate with Manurhin. We waited anxiously for 16 days for his reply. Finally, we found out that he was coming to London to represent then Prime Minister, Mr Lee Kuan Yew, for the Commonwealth Prime Ministers’ Conference which was to begin on 6th September 1966. Sir Hartnett, Mr Robert Lee and I went to the Heathrow Airport VIP lounge and waited

anxiously for his arrival. He was surprised to see us, and even more surprised when we told him that we did not receive his reply to our telegraph report. He said that he had replied by telegraph immediately instructing us to proceed accordingly. We were delighted and immediately departed for Mulhouse to negotiate with Manurhin and placed orders for the full line of machinery to produce small arms ammunition. We wondered what happened to Dr Goh’s telegraphic instructions.

Filled with excitement of having our own and Singapore’s first small arms ammunition manufacturing plant, we returned to Singapore and very quickly and enthusiastically, formed CIS and planned for the construction of the factory at Jalan Boon Lay.”

One of the first specifications prepared by the TEA Section, Logistics Division was for the manufacture and acceptance of 5.56mm rounds. As the 5.56mm round had not yet been accepted by any army in the world, there was no specifications from other established armament authorities in the US and NATO to adopt for our use. The 7.62mm round was then the standard round in the US and NATO, and specifications for its production and testing were available.

The defence engineers of the TEA Section used the NATO specifications of the 7.62mm round as reference in the preparation of specifications for 5.56mm round that CIS would be producing. To make sure that the product would be of a standard comparable to that of NATO’s 7.62mm round, engineering judgement was used to tighten the manufacturing tolerances. CIS had to work very hard to manufacture the 5.56mm round to meet these specifications. Mr Lai Chun Loong, a young engineer responsible for quality assurance, established procedures to ensure that the product would meet all the specifications on delivery.

On completion of the first batch of 5.56mm

rounds, CIS invited the TEA Section to test them at the CIS test range at Jalan Boon Lay. The testing officer fired the AR-15 rifle in the single round firing mode and found the rounds hitting the target as to be expected. He then switched to the automatic mode and after a few rounds there was an explosion. The casing of a round had ruptured in the chamber with bits of brass flying out when the casing was ejected. Some bits of the brass casing found their way into the arms of the testing officer.

This first lesson on ammunition testing was learnt by the TEA Section with the promulgation of a safety rule forbidding firing of any new weapons and ammunition by testers. The weapons and ammunition must first be tested on a stand with remote firing. This rule would only be lifted after the weapon had been tested and found to have met all the specifications on a testing stand.

The cause of the explosion was found to be due to overfilling of explosives in some of the rounds. This problem of overfilling was quickly addressed by CIS. Series production for the SAF began soon after. Samples from every batch were tested and witnessed by inspectors from the TEA Section before acceptance by the Logistics Division for delivery to the ammunition storehouses of WAOB.

Unexpected Consequence of the High Specifications for 5.56mm Round

The mass production of 5.56mm rounds began in August 1967, but only after everyone involved was confident that the tools and dies were perfect and tests of the ammunition parts and completed ammunition showed perfect results according to military specifications; accuracy and perfection were critical and could not be over emphasised or compromised.

As there were precision machines to make tools and dies for the ammunition plant, Dr Goh added another manufacturing plant that needed precision tools and dies and the Singapore Mint was built on a 25-acre land. To the delight of the management and staff, the Mint could start minting the Singapore coins in March 1968.

CIS was very focused and had only one goal then and that was to make the production of the small arms ammunition and minting of the Singapore coins a success. Everyone in the company was united, worked very hard, had courage to make difficult decisions, cooperated and contributed as one family to ensure the success. It was a very happy and proud day for all when Dr Goh officiated at the opening of CIS on 27th April 1968.

Following Dr Goh’s decision that CIS should produce the AR-15 rifle a team from Colt Industries came to Singapore for site survey and negotiations. They visited CIS and were impressed by the modern plant and air-conditioned filling room for the ammunition. They asked if they could test the 5.56mm rounds with the AR-15 rifle that they had brought with them. They went to the firing range and did their usual series of demonstration firing with the CIS produced rounds. They were surprised by the accuracy of their shots. They wanted to understand the reason and asked to see the specifications of the ammunition. They then told us that the specifications were similar to that used in the US for “match ammunition”, rounds prepared by hand for shooting competitions. They bought a sizeable amount of 5.56mm rounds from CIS for their AR-15 rifles in demonstrations to other potential customers like South Korea.

This was a pleasant surprise for the TEA Section as it showed its practice of erring on the side of more safety had additional benefits beyond safety.

Pioneer Armament Engineers

One of the pioneer armament engineers of Singapore is Mr Lai Chun Loong. In 1967 he returned to Singapore upon completion of his degree in Mechanical Engineering from the University of Auckland under a Colombo Plan Scholarship. He graduated in three years instead of the normal four years of study.

Given a choice by the Public Service Commission to work in an engineering company or in a government department like the PWD he selected the former. As a graduate he was liable for NS and he reported to CMPB (Central Manpower Base) for his enlistment. After enlistment, Mr Lai was instructed to report to CIS. When he arrived he found the factory was still under construction, and fitting out was in progress. He started work at CIS from March 1968 and was appointed as an engineer in charge of Quality Control and began his education on production of bullets on-the-job. He learnt by doing.

The equipment for the production plant was brand new, ordered for the project by the contractor of the plant Manurhin. The measuring and testing equipment in the Metrology Department were of the highest quality and precision to meet the stringent standards that CIS would be achieving. The job was a mechanical engineer's dream, to participate in the development of the most modern precision engineering company of Singapore.

The 5.56mm round that Manurhin plant would be producing was not yet a standard round of NATO and therefore there was no common standard for acceptance by the Logistics Division. As customers were king, Mr Lai took the acceptance specifications from the TEA Section as given and worked hard on the production tolerances to ensure the products would meet the specifications. This was a challenge but Mr Lai rose up to it and production proceeded.

With each project, Mr Lai learnt valuable lessons and built up his engineering judgement and self-confidence. He learnt that customers had a tendency to over-specify their requirements. Their cost-benefit analysis was skewed towards performance over cost. But CIS as a commercial entity had to be mindful of costs, profitability and sustainability. The company could go bust if it did not watch these factors with the eye of a hawk.

The self-confidence and engineering capability of Mr Lai are best illustrated in the following event. Around 1975, Oerlikon Machine Tool Works of Switzerland needed additional manufacturing capacity for its world beating anti-aircraft gun, the Oerlikon 35mm twin gun for an international market. Oerlikon had sold 24 twin guns to Singapore in 1969 and it got to know the capability of CIS in the development and production of top quality armament products. It assessed that CIS would be able to produce the 35mm ammunition. Mr Ong Kah Kok, then chairman of CIS, negotiated a contract with Dr Buhler, Chairman of Oerlikon, in Switzerland. On his return, approval was sought from then Minister for Defence Dr Goh for the first export sale of CIS. Mr Lai gave the briefing and answered questions on contingency plans to meet CIS' contractual obligations. When asked what was the critical equipment for the manufacturing process, Mr Lai answered that it was the 1,000-ton May Press that would be needed to make the steel cartridge case of the 35mm round. There was only one 1,000-ton May Press in Singapore. He ordered Mr Lai to buy another 1,000-ton May Press.

Mr Lai was not happy with the decision as, with all the preparation for contingencies made, he did not see the need to spend a million dollars to buy another 1,000-ton May Press as insurance. As there was no assurance of a repeat order from Oerlikon, CIS would be burdened with a 1,000-ton "white elephant". The General Manager Mr Cyril Olsen did not want to be responsible for disobeying

the order from Dr Goh and asked Mr Lai to explain to the Minister. Mr Lai made the case on how his contingency measures would be adequate, and why the 1,000-ton May Press should not be bought. Dr Goh accepted the recommendation and rescinded his order to buy the 1,000-ton May Press.

Years after CIS began making the 35mm rounds under licence for Oerlikon, Mr Lai found out why Dr Goh had recommended buying the second 1,000-ton May Press to ensure production could continue even if one press failed.

"I was surprised that Dr Goh was willing to invest in another May Press because he was very careful about spending money," said Mr Lai. "Years later, I found out the reason for that decision. He told me in one casual meeting, 'The reason I was so careful with the first overseas order you guys obtained was because we could not afford to fail. If we had failed in this first export order, we might as well close shop.'" The reputation of CIS was more valuable than the price of one May Press.

Mr Lai added, "If we had fouled up the first order, we were finished. It seemed like a rash decision to buy a second May Press, but looking at it from the big picture, it was a careful and considered move with the company's reputation at stake. Again, there was no cost-benefit study; it was a case of 'just do it'."

Noting that the May Press argument was the first time he "disagreed" with Dr Goh, Mr Lai said, "That episode helped me gain his trust, because I reasoned with him on the issue of the May Press and did not give in. In retrospect, I was proven correct."

Production for the order to Oerlikon began soon after. The technical capability, sound judgement and self-confidence of Mr Lai were recognised and with time he rose up

to become President of CIS.

His greatest contribution to the development and production of armament for the SAF and international market was in the creation of a culture of innovation and enterprise in the engineers of CIS. He decided that, as research and development would be fundamental to the future of CIS, he would build up its Engineering Department. He found the engineer who had the leadership qualities and technical competence in then LTC Henry Cheong to build the Engineering Department. Despite opposition from his colleagues he boldly allocated 1% of the company's revenue into Engineering Department.



Then LTC Henry Cheong, circa 1969

Mr Lai recall, "Henry Cheong completed his MSc in OR and Systems Engineering in 1975 under the SAF Fellowship Programme. He was persuaded to join CIS around 1977 as the Product Development Manager.

The first act of Henry was to excite young engineers to join him to develop new armament products. CIS was running out of office space, and did not have many engineering facilities then, just a tool room

making tools for the ammunition factories.

As the team was built up we need space to house them. I took the decision to convert the space above our canteen to house these technical staff. Then we spent money to buy equipment such as the computer-aided design and manufacturing (CAD/CAM) systems. Henry set up the CAD/CAM unit; the technology was pretty new in those days. Later we added more sophisticated equipment such as velocity measuring equipment and high speed cameras. These were expensive equipment to purchase and there was no external financial support. Funding was taken from the bottom line of CIS.”

Mr Lai added, “As the team grew and new products were introduced CIS brought in more technical staff. At a point in time CIS had more than 300 engineers and technicians. The more promising ones were sent overseas for further studies and training.

To support the R&D efforts I set aside 1% of company's revenue to the Engineering Department to fund the initial concept studies. Salaries were not high in those days, so the sum of money budgeted helped us to move forward. I met with some resistance from fellow colleagues who were unhappy that the company was spending so much on the engineering effort. The return had yet to be seen in those early days.

When a project had traction or good reception from MINDEF, a supplementary budget was set up to fund it. MINDEF sometimes helped with some funding at this stage.

Dr Goh paid a lot of attention to what we were doing. He pushed us to make more parts for the M-16 rifles and also was instrumental in getting us started with the Ultimax 100 programme. He gave Philip Yeo, then Deputy Chairman of CIS, a free hand to drive the growth of the company along.

Every year we would hold a dinner for Dr Goh to showcase our new products. This was usually held in a function room at a hotel. Dr Goh enjoyed playing with those new products.

Before I left CIS in September 1993, I wrote a paper to ask that the Engineering Department not be disbanded. In the paper I explained how we had painfully put this team together and its importance to the defence industry. I concluded by saying ‘once it's disbanded it will be impossible to put them back again’. I wrote this paper as I heard rumours that the Engineering Department would be downsized after I left.”

Manufacture of Mortar Bombs

On Saturday 27th April 1968, Chartered Industries of Singapore was officially opened by then Minister for Defence Dr Goh Keng Swee. In his speech, Dr Goh stated that they were witnessing the first-stage of the development of the company, the production of small arms ammunition and coins. He announced that Chartered Industries had entered into a licensing agreement with Establisement Salgad of Finland for the production of mortar bombs. He continued, “This is a considerable undertaking involving a total investment of \$15 million on plant and equipment. First stage production will commence at the end of this year and the full production line is expected to be completed by the middle of 1970. There are also other proposals now under consideration with European armaments manufacturers. All things considered, this promises to be one of the growth industries of Jurong. Further, because it is the first large-scale venture into precision engineering in Singapore, local industries will benefit by the expertise that will grow in the tool and die workshop.”

Phase 1 of the manufacture of 81mm mortar bomb bodies and tails in the machine shop of CIS at Jalan Boon Lay began in 1968. The filling of the mortar bombs with their TNT explosive charge could not be done at Jalan Boon Lay as the safety distance for the TNT filling plant was large and could not be accommodated there. A new filling plant would have to be built. As the SAF would also require a large amount of demolition materials and mines there was also a need to produce TNT. CIS therefore built a plant for the manufacture of TNT and for the filling of mortar bombs in the Bukit Timah Nature Reserve, next to the ammunition depot of the SAF.

81mm Mortar Bombs Dropping Short

Even as the production of 5.56mm ammunition and mortar bombs got off on to a good start, defence engineers had to troubleshoot problems as the young Army gained experience using weapons and ammunition in local terrain and climate conditions.

There were training reports that some bombs fell short of the targets when 81mm mortar bombs were used to engage targets at short ranges with low charges in the Pasir Laba Live Firing Area. This was a critical defect which was not observed during acceptance tests that were done with higher charges to verify the dispersion of the rounds at the maximum range.

One of the theories for the rounds dropping short was that the propelling charges were wet because of rain falling on the bombs. A test was done with bombs that had become slightly damp after watering with a watering can. This had no effect on the bombs and they hit their targets. The test was repeated with the charges almost soaking wet. This test almost ended in disaster with the bomb falling about 50m in front of the mortar. Luckily for the testing team, the fuse of the bomb did not arm as the velocity of the bomb did not reach the level for the arming mechanism to be unlocked.

This was another lesson learnt by the hard way during testing: Do not conduct a test without taking into account all the possible consequences. A dummy round could have been used for this test but was ruled out as the range practice would require all “blinds” (unexploded bombs) to be found and disposed. Looking for blinds was not one of the tasks that TEA testers enjoyed doing and so a live round was used in the 81mm mortar bomb test. Another testing rule was that live rounds should not be used if dummy rounds could be used instead. Spending time looking for

a dummy round in the target area would be better than having a live round exploding prematurely on you.

A second theory was that when the bomb was loaded into the barrel air pressure could move the small number of charges up the body of the shell to above the flash holes resulting in incomplete combustion. A test was done with charges tied to the bomb body and with one charge above the flash holes. The bomb dropped short at around the same distance as that observed in earlier training exercises. This was confirmed by repeating the test.

The fix to the rounds falling short was relatively easy with the addition of a metal clip to be used for low charges to prevent the charges from moving up the bomb. This modification was tested and the problem was solved. This requirement for a clip was incorporated into the specifications of the 81mm mortar bombs. Ammunition technicians inserted clips into the containers of rounds that had been accepted and kept in ammunition storehouses.

Manufacture of M-16S1 Rifles

The manufacture of M-16S1 required more precision engineering capability than that needed for the manufacture of small arms ammunition and mortar bombs. The tolerance of weapon parts had to be very tight to meet the parts interchangeability requirement. The receiver was made from aluminium alloy casting and machined. CIS was initially licensed to make 11 parts. The remaining parts were purchased from Colt's suppliers. With the engineering capability and production capacity more parts could be made in CIS to reduce the unit cost of M-16S1.

There's a side story to what triggered this decision. A young CIS engineer, Mr Lai Chun Loong, was summoned to Dr Goh's office, with orders to bring along an M-16S1 rifle. He did as he was told and drove to MINDEF

in Tanglin with the rifle in his car boot.

"Why should the Minister call me? I was just a junior engineer," Mr Lai recalled. "At the same time, I was excited about the whole idea of meeting up with the great man. And nobody knew what he wanted to do with the rifle, which was even more worrying!"

In Dr Goh's office, the Defence Minister asked Mr Lai to strip the rifle to its components. Mr Lai was then asked to separate the Singapore-made components from parts made overseas, and then to further segregate the high-value parts from the low-value ones.

Mr Lai noted, "Dr Goh proceeded to ask, 'Why aren't we making this? Why aren't we making that? Why?' His constantly asking us 'why' was a way of challenging us. 'Why aren't we doing this or that?' That really got our minds thinking."

Dr Goh found that the costs of some of the small parts were very high – parts made by a new manufacturing process known as "Investment Casting". In 1974 he sent the General Manager of CIS, then Mr KC Oei and Director Logistics, then LTC Lui Pao Chuen, to South Korea to learn how to make M-16 parts cheaper. The South Korean Ministry of National Defence had an arsenal in Pusan that manufactured weapons and ammunition to meet their needs. Its Director Logistics Bureau was a Major General of the Republic of Korea (ROK) Army. The arsenal was under the command of the Commanding General of the ROK Army's Logistics Command. The M-16 manufacturing plant was completely integrated, with raw materials like aluminium ingots, and steel and plastic coming into the receiving bay of the plant and completed M-16s leaving. The plant had a much higher level of automation as compared to CIS, with production rate at about five times higher. Investment casting was not a complicated manufacturing and could be done by CIS, but the cost of producing M-16S1 by CIS

could not be reduced significantly with the purchase of semi-finished parts for processing and final assembly.

Dr Goh had determined at the start of the M-16 programme that CIS, on completion of the licensed production of M-16S1, would need to produce another assault rifle to sustain the production capability. For CIS to be able to sell this assault rifle overseas it had to be affordable. An international search for designs of low-cost assault rifles ended with the selection of the Sterling's Light Automatic Rifle (LAR). It was produced by CIS as the SAR-80. The SAF bought limited quantities of the SAR-80 as it was heavier than the M-16S1 and did not have superior performance. It did not replace the M-16S1 as the standard assault rifle of the SAF.

It took about 10 years of more R&D before the M-16S1 was knocked off its perch by the SAR-21 assault rifle in the early 1990s. The SAR-21 was designed and developed by CIS with Defence Technology Group (the predecessor of DSTA) and the SAF. It was officially started in January 1992 and completed in 1998. The tripartite project team spent the six years working out the requirements and testing various prototypes before the design freeze resulted in the first production batch of SAR-21s in 1998. That gestation period resulted in a bullpup rifle which was shorter than the M-16S1, yet retained the same barrel length as the M-16S1 for firing accuracy. The SAR-21 was put in-service in 1999 with the SAF and remains in-service till today.

The SAR-21 is a highly innovative product and ergonomically designed to suit the Singaporean soldier. Being reliable in performance also provides confidence to the soldier as part of a positive psychological defence. Compact and rugged, the SAR-21s made their public debut at the 1999 Army Open House in dramatic fashion with SAF demonstrators throwing the rifle on the ground to show how tough it was.

The SAR-21 is designed with a long stroke gas piston and rotating bolt operating system which provides very low recoil for good controllability during firing. Its integrated factory zeroed 1.5x magnification optical sight and laser aiming device enable soldiers to achieve high hit probability and easy target acquisition. Its tough translucent polymer magazine enables ammunition status to be known, and has a patented Kevlar shield and a vent hole to protect the firer in an unlikely event of a chamber explosion. The SAR-21 has a family of weapons comprising the up-to-date modular mounting system variants that has a set of Picatinny rails for mounting of accessories for various mission requirements, M203 under barrel variant and marksman variant with 3x magnification aiming scope for infantry support. The SAR-21 is also exported and adopted by countries such as Botswana, Brunei, Morocco, Peru and Timor Leste, and also fielded by the special forces of several nations worldwide.

Licensed Production of Anti-Aircraft Guns and Ammunition in Mid 1970s

With the acquisition of the best land-based anti-aircraft guns, the Swiss Oerlikon 35mm twin gun for SADC and the best naval anti-aircraft guns, the Swedish Bofors 40mm gun for the Singapore Maritime Command, there was opportunity to produce some of the guns, assemblies and ammunition in Singapore. Oerlikon was the partner of CIS and a joint venture Allied Ordnance of Singapore (AOS) was set up with Bofors. The contract manufacture of Oerlikon guns and Bofors guns and ammunition gave a boost to the precision engineering capability of Singapore. Making the world's most advanced anti-aircraft guns built up the self-confidence of our engineers. The belief that they could design the best 155mm guns in the world if they were given a chance to do it.

Extended Range Mortar Bombs

Around the early 1980s, the Engineering Department of CIS moved from research to in-house design and development of products.

Mr Lee Chuen Fei, an armament engineer who served in CIS from 1978 to 1996, recalled the many conversations he had with his mentor, Mr Henry Cheong, then Director of Engineering Department², on refinements needed to give mortar bombs a longer reach. Mr Cheong's mandate was to explore and expand the type and number of CIS armaments and ammunition products.

Mr Lee said, "On a number of occasions, Henry talked to me about extending the range of the 81mm mortar bomb. He described the CG (centre of gravity), flight trajectory and flight stability of the mortar bomb. I had no idea what he was talking about then and to keep on par with Henry I started reading up the Oerlikon Handbook and magazines which he passed to me. I also referred to the US Engineering Design Manual AMCP Series for Ammunition Design from our CIS Library. We did not have the luxury to check things up on the Internet then. We did not even have a desktop computer."

Mr Lee and the CIS team streamlined the aerodynamic profile of the standard 81mm mortar bomb, and then developed a propulsion charge system to optimise the launch pressure and gave the prototype extended range (ER) bomb an appropriate length of tail fin to provide flight stability along with a leading edge to the tail fins to reduce drag.

Mr Lee recalled, "Computer simulation tools were primitive then and the only computing device we had was the mainframe computer used by finance and human resource

² Mr Henry Cheong was promoted to Senior Vice President in 1991 and then to Executive Vice President in 1996 and concurrently Director of Engineering at Singapore Technologies.

departments. I refreshed my memory of Fortran and Basic programming languages to aid the design of the mortar shell walls to withstand the launch stresses, and to simulate the trajectory of the projectile to ensure that it remains stable during flight. The optimum amount of propellant charges and burn-rate must be determined to keep within the safety chamber pressure limits of the mortar barrel yet achieve higher muzzle velocity to extend the range."

Mr Lee added, "I remember visiting Prof Shang Huai Meng of the National University of Singapore (NUS) who was my lecturer in Mechanics of Solids to consult him about the formulas given in the Engineering Design Manual so that I could use them for developing computer simulation software to compute stresses. In those times, FEM (Finite Element Methods) was a luxury and beyond reach. I also visited Mr Teng Ngai Huat and Mr Lim Liat at Defence Science Organisation (DSO, now known as DSO National Laboratories) to consult them about point-mass trajectory simulations before developing the trajectory software for mortar bomb in Fortran language."

We see here that even in the early days of Singapore's defence industry, close collaboration with research institutes and MINDEF agencies such as DSO was a critical element that underpinned our defence projects.

"The culture for innovation was very conducive," Mr Lee noted. "Henry was very hands-on. I remember people calling him the mad scientist. He constantly came up with his vision for new products. The engineers in the Engineering Department did not fear being reprimanded for making mistakes. When they encountered an issue, Henry would call them up to debate on "What could be done to solve the problem? Why was it done this way?" There were coarse words (that's his nature, not intentional) but he never intimidated so

we would not find excuses for not trying."

If project risk management methodology had been available then, the project team could have saved some development time by addressing the potential issues, critical components, critical lead time and establish the priorities, instead of depending too much on a trial-and-error approach.

CIS had a very well equipped tool room with experienced machinists. They could machine any prototypes like test barrels for measuring the pressures using piezo-electric gauge, the mortar shell bodies, the fins from solid aluminum bars or extrusions.

For measuring the Pressure-Time curves in the barrel, CIS used piezo-electric gauge tapped into a special thick barrel and tested at the Baffled Range at the CIS Rifle Range Complex.

For range testing, SAFTI range dates were allocated mainly for weekend testing. The CIS ER bomb project team burnt many weekends to conduct range and dispersion verification testing, lobbing bomb after bomb and closely measuring their effects in the impact zone. High explosives were not allowed for safety reasons, therefore the prototype bombs for spotting purpose had to be manually filled with TiO₂ (Titanium Dioxide) by hand at the Rifle Range Complex, also during weekends in order not to affect the daily production operations. The result of their efforts was an ER bomb that improved the range of the 81mm mortar, giving the mortar team the ability to hit targets from a greater distance in support of army operations. This increases the mortar team's survivability, as mortar barrages can be delivered further away from the enemy's frontline and adds to the shock effect of mortar attacks.

Extended Range 155mm Artillery Round

In the late 1980s, CIS started to design the 155mm Extended Range Full Bore with Hollow Base (ERFB-HB) and with Base Bleed (ERFB-BB) rounds, to enhance the artillery firepower by extending the range from 19km³ to 30km fired from the standard 39-calibre howitzer.

ODE was concurrently developing the 52-calibre artillery howitzer which could fire the ERFB-BB round to reach a range of above 40km.

The ERFB round was said to be originated and designed by Dr Gerald Bull from Space Research Corporation, McGill University, Canada. It was reported that due to his involvement in Project Babylon "supergun" for the Iraqi government, Dr Bull was assassinated outside his apartment in Brussels, Belgium in March 1990. Different from the conventional artillery M107 round which was also produced by CIS, the ogive of the ERFB round was streamlined from the front all the way down to the copper band to achieve the aerodynamic profile. This profile presented a conflicting requirement as the round needed to be supported at two sections along the barrel during launching. The four nubs were angled to match the flow around the projectile rotation during flight. There were two possible options to attach the four nubs to the projectile so that these nubs could ride on the inner rifling of the barrel and provide the necessary support during the launch of the projectile to supersonic speed of almost 900 m/sec (Mach 2.6).

The nubs could either be welded to the round or machined from the projectile. The relatively thinner shell wall meant that we had to use tougher spring steel 9260 as

³ 19km is the range of the standard M107 HE round fired from the standard 39-calibre howitzer.

compared to the 1050 steel. CIS decided on the latter due to concern that welding could introduce quality issues such as welding defects. CIS's manufacturing capability was also stronger in machining as compared to welding. ED's forging process specialist Mr Hui Tee Jong developed the forging and machining processes to establish the preformed shape of the spring steel projectile to minimise the machining process. CIS purchased special Computer Numeric Code machines – computer-controlled machine tools - to fabricate the nubs, special ultrasonic machine to perform 100% check to ensure no cracks along the shell body during the forging, and machining processes and auto-gauging machine to measure the tolerances.

Despite having a full ogive optimised aerodynamic profile, the projectile could only achieve up to 24km with a hollow base unit. To reach the target 30km, the hollow base unit was replaced with a Base Bleed unit (BBU). The slow-burning base bleed propellant would generate gases that emerge from the central hole at the base at subsonic velocity and fill up the vacuum at the base. This would inhibit the formation of turbulence behind the projectile base that would induce drag.

CIS had two potential suppliers for BBUs: SNPE from France and Somchem in South Africa. These suppliers also manufactured propellant charges. Somchem's charge called the C30 (for 30km range) used a combustible sleeve to house the stick propellant and that would moderate the burning rate and reduce the heat transferred to the barrel. Due to the charge's solid structure, automatic loading was also possible.

Mr Lee Chuen Fei, who was part of the CIS team that developed the long-range 155mm rounds, said, "I remember my first trip to South Africa to compare and evaluate the two types of Base Bleeds (SNPE's vs Somchem's). Our objective was to measure the range and dispersion achievement between the two

BBUs. The firing test of the two series at Alkantpan Range had to be conducted one in the morning, and one in the afternoon. Somchem proposed to test one series from one source in the morning, and the other source in the afternoon. The wind speed, direction and air temperature were quite different between morning and afternoon. I suggested mixing the projectiles of two series in a randomised manner so that we could compute and rule out any environmental influences between morning and afternoon. Prof Goh Thong Nee taught me Design of Experiments in Statistics during my MSc (Industrial Engineering) course at NUS and I understood that randomisation is very critical when doing such tests. The 6-foot tall gigantic Range Expert had insisted to do it his way but I refused to relent and stuck to my position. He was angry, but fortunately I was the customer. Eventually I was able to compute and obtain meaningful test results by segregating the environmental factors between the two series of tests. He was then convinced and when we met in subsequent trips, there was a look of respect in his face and we became good friends."

In various projects throughout the years, the men and women who were part of our defence eco-system went through trial by fire and had to stand their ground many times. By 1995, a family of 155mm ER Artillery projectiles were delivered to the SAF. It complemented ODE's new 52-caliber 155mm FH-2000 Howitzer.

Yet, more improvements were planned by the Engineering Department team.

Life Extension of AMX 13 Light Tanks

In the mid 1980s, the Army had to make a major decision whether to replace the AMX-13 with a more modern tank or to do major upgrades that will extend their service life by another 15 years. With escalating cost of military equipment the replacement of

the entire fleet would be very costly. A new engine, automatic transmission and suspension would improve the light tank's reliability and mobility. The firepower could be improved with the replacement of the 75mm high-velocity gun by a 90mm Cockerill medium velocity gun firing more effective HEAT ammunition. The innovative solution would be the development of a 75mm round that would have the same penetration power as the 105mm gun. The savings that would be achieved with delaying the purchase of new tanks would be very substantial. Advances in technology would also provide greater effectiveness at an affordable cost. This was the challenge that the Engineering Department set out to conquer. Mr Lee Chuen Fei was the armament engineer who climbed the Mount Everest in the development of the 75mm Armour-Piercing Fin-Stabilised Discarding-Sabot with Tracer (APFSDS-T) round.

Design and Development of Armament for Fighter Aircraft

The development of upgrades to the A-4B Skyhawk fighters was done with very little participation from our Air Force pilots. The A-4B had been decommissioned by the US Navy and mothballed for storage at Davis-Monthan Air Force Base in the Arizona desert, the graveyard of US military aircraft. Lockheed had been contracted to refurbish two squadrons of A-4B Skyhawks and to upgrade their firepower. Our pilots had been operating former RAF Hawker Hunter fighter aircraft since 1970. The Hunter was armed with four 30mm ADEN guns each with 150 rounds of ammunition. The fire power of the Hunter fighter was awesome. The A-4B Skyhawks were armed with two 20mm guns.

Our pilots demanded that the firepower of the A-4B Skyhawks be upgraded with the replacement of the 20mm guns with 30mm guns. This was done by Lockheed and our A-4S (as the upgraded A-4B was designated)

began life with two 30mm guns. During live-firing exercises it was found that the RAT (Ram Air Turbine) would be deployed. The high stress to the airframe would cause the lock of the RAT to be released. After much testing and modification this problem was contained. It was then found that cracks in the aircraft structure were beginning to appear. With great reluctance the Air Force decided to give up the 30mm guns and to revert to the 20mm guns.

The use of 70 mm rockets was their solution to replace the loss of the 30mm guns. CIS was asked if they could develop 70mm rockets for A-4S. The Engineering Department studied the proposition and decided that the capability of producing rockets would be important for the future growth of the company. Despite the weak business case, the capability development case was strong enough for Mr Henry Cheong and his group of engineers who had a bent in rocket engineering to take on the development project. Mr Lee Kah Hoo was then a young engineer who had just joined CIS. His account of the learning by doing in rocket design and development will be an inspiration for innovators to dare to dream and dare to do.

Armour-Piercing Fin-Stabilised Discarding-Sabot with Tracer

By Mr Lee Chuen Fei

Armament engineer Mr Lee Chuen Fei gives a first person account of the development of Singapore's first sabot round for the SAF's tank battalions. In its time, the 75mm armour-piercing fin-stabilised discarding-sabot (APFSDS) round was the most powerful anti-tank round for the AMX-13 light tank.

It was not easy to establish a set of realistic performance objectives with the demanding user. We managed to compromise to agree that the APFSDS penetrator must penetrate 240mm of rolled-homogeneous armour (penetrate means able to see light from the other side after penetration) at a range of 1.2km with an accuracy measured in milrad. When the penetrator hits the armour plate at a speed of 1100-1200 m/sec (more than three times the speed of sound), it melts its way into the armour plate and the whole length of the penetrator is spent along the path of penetration. The massive kinetic energy is transferred to the target during the penetration stage. This penetration phenomenon is very different from a small arms bullet penetration.

During the initial stage of the development, many penetrators broke up and slapped themselves onto the armour plate. I was fortunate to have attended a munitions seminar overseas in the US during that time and discovered that the primer played a significant role in the initiation of the propellant for the APFSDS. The propellant was the high energy M30M multi-perforated grain but it also created stress waves during the burning process. The stress waves would be strong enough to break the penetrator. I learnt that the propellant should not be ignited in the conventional way at the base of the cartridge, which was the case in conventional high explosive round using another type of propellant. We developed a long primer which ignited the propellant from the centre of the propellant column. Initiated from the centre

of the column, the propellant would burn both ways towards the back as well as the front simultaneously. My boss initially was not convinced with this explanation but I did the trial anyway to prove this theory. The results were amazing. There was no further breakage of any penetrators after we started using the long primer with centre initiation of the propellant.

I can never forget one critical event involving the range and dispersion accuracy testing, towards the later part of the APFSDS development. Some of the staff went two weeks before the test to engage contractors to fabricate all the mountings and concrete base set up for the rolled-homogeneous armour plates we shipped there. They also erected the huge target frame for aiming the gun, made from plastic floor mattresses that used to be popular in kampong houses. The 10m by 10m target looked small 1km away.

During that test, the then Chief of Armour COL Patrick Choy attended. That morning, all the APFSDS rounds hit low and badly damaged the concrete supporting the base of the armour plate mounting. Fortunately the grouping looked reasonably good from the mattress frame in front of the target. COL Choy suggested we go for an early lunch to discuss the best action. During lunch it suddenly crossed my mind that once an "Encik" (Warrant Officer) from Armour told me that the older AMX-13's elevating gear was sensitive to its direction of travel. That means we need to bore-sight the gun by setting the barrel from bottom up so that the elevating gears would be fully engaged and there would be no backlash and therefore no gap between the gears. Otherwise the barrel could droop down. We needed to bring the barrel from the bottom and elevated it upwards till it reached the point of aim. After lunch we tried exactly this for the next group of APFSDS rounds and all of them landed on the armour plate with good grouping. The joy was fantastic. COL Choy was so glad and praised the design.

Development of 70mm Rockets

By Mr Lee Kah Hoo

Armament engineer Mr Lee Kah Hoo recalls the CIS efforts to develop Singapore's first 70mm aerial rockets for the Republic of Singapore Air Force (RSAF). Then newly-graduated, Mr Lee and CIS colleagues found novel ways to acquire know-how in rocket artillery with the help of foreign partners.

It was probably around 1986/7 that I started to read rocket-related literature handed to me by Mr Henry Cheong, then Director of Engineering Department in CIS. I also found myself travelling to places where rockets were made. Visits to such facilities were always via government channels at least at that time - maybe because rockets were regarded a class higher in awe and science compared to guns and their ammunition, and hence commanded more secrecy and security. Nevertheless, the memories were priceless.

The technologies required in rocket propulsion are very different compared to gun systems. For rocket artillery, other than the solid propellant rocket motor and warhead (usually sub-munitions), you need a fire control system (FCS) and a mobile launcher to aim the rockets in the right direction in three dimensions. The FCS has to be programmed to account for, among other things, the wind, the intended range and the required arming time. You also need specialised vehicles and equipment to stabilise the launcher, and to transport and transfer the rocket loads.

It was quite far-fetched to expect CIS to venture down that technology road at that time. We could surely make the sub-munitions but that was not a new capability. Although the system hardware (FCS, launcher, vehicles) could be purchased or modified from available hardware, the exciting new thing was in the rocket motors. But realistically, the Army's requirement for 70mm free-flight aerial rockets as part of a US\$10 million order would not make economic sense. Also, where and

how much could you train to fire the rockets to be able to generate replacement orders to sustain production? However, our local defence industry had ambitions, and rockets and guided munitions were the natural next steps as we progressed up the technology ladder to develop new products. My view was that they would add on to our strategic capabilities.

We progressively assembled a team of about 10 mechanical and chemical engineers, and chemists for the project. Except for a chemist with a Masters' degree and some work experience, the CIS team comprised mainly fresh graduates with no experience in ammunition development. Getting someone knowledgeable to guide us was thus expected and necessary.

Such expertise came from our foreign partners. We knew the Swiss defence company Oerlikon Contraves pretty well and they recommended a retired staff with rocket propellant expertise as a consultant. The computer program that allowed us to do stress-strain analysis for the polymer-based combustible composite was sourced from an Italian company. Two of our staff went to Rome to learn to use the code and brought home the program, which was vital to optimise the formulation and mechanical properties of part of the rocket.

For the launcher, I had to visit Harvard Interiors, a US manufacturer based in St. Louis, Missouri, many times to convince its 60-ish CEO to sell us the parts. At that time, Harvard was a premier maker of chairs and I could not figure out why the US authorities would continue to allow it to make military launchers. It was interesting to watch their chairs go through various auto load cycling tests to measure the chairs' reliability and durability. On each visit we would discuss many worldly things but he would still not sell us the required parts and would not say why. Finally, on one such visit, he relented. It was a big relief, as it was the last material

on my shopping list. Not only did he sell us the parts, he also allowed a CIS production manager there to learn the launcher assembly process from paper tubes, wire harnesses, intervalometers, bulkheads and fairings.

Interestingly, CIS was not the only organisation in the region that was developing rocket technology. Thailand was already experimenting with various ammunition developments and we shared what we knew with each other. In addition, the Thais opened their ranges for us to test out stuff. Our mutual aim was to combine our respective requirements for economies of scale.

We fired the prototype rockets into the open sea from a launcher securely mounted on the beach and with carefully positioned radars, high-speed cameras and flash-photography equipment to capture each shot. There were usually fishing boats a few kilometres out in our line of fire, and although pre-warned they would not move even with additional sirens and warnings with loudspeakers. With the Thai safety officer's permission, we would fire a rocket out to sea, and on hearing the rocket blast and seeing the smoke trail whizzing in the air, they then scurried away. After a few scares they were back again, probably confident our rockets would never reach them. A few rockets simply exploded on leaving the launcher.

As we progressed we conducted more stringent tests - aging studies (temperature cycling for service life correlation), vibration, shock and drop tests – to stress-proof our motor design. Statistical samples from batch production went through thorough qualification tests to achieve the required reliability confidence levels. The long series of ground tests took over three years to complete.

The final hurdle was testing the rockets from an RSAF aircraft. First we had to ensure our in-house assembled launcher then with a load of rockets could be safely carried in flight.

Soon our rockets were fired and tested for flight integrity and dispersion, with an ace pilot hitting the bullseye! Incidentally, a few months after our last and final test in Korat, the hotel our staff usually stayed at collapsed and killed more than a hundred people. That was sometime in August 1993. We were lucky.

Quantum Leap in the Development of Armaments

CIS experienced a number of hits and misses with its range of infantry weapons designed for the SAF. Thankfully, its successes outweighed the dud projects, giving rise to a firm foundation on which the present-day ST Kinetics built its capabilities, product lines and reputation for excellence in 40mm high and low velocity grenades and bullpup weapon technology.

The SAR-80 5.56mm assault rifle was the first assault rifle that was designed overseas and manufactured in Singapore. It was not a success, with the SAF buying only a relatively small number for use by logistics units and the military police, including the contingents guarding the Istana.

The Ultimax 100 section automatic weapon (SAW), on the other hand, was successful in sales to the SAF and foreign military forces. Two American designers – Mr James Sullivan and Mr Robert Waterfield – helped CIS with the design of the Ultimax 100, which was adopted as the Army's first SAW. These small arms experts brought a wealth of experience to CIS as Mr Sullivan had been part of the weapons design team for the AR-15 rifle, which evolved into the M-16 rifle.

The SAF liked the Ultimax 100 for its lightweight, low recoil and ease of use even when firing sustained bursts from its 100-round drum magazine. In addition, the 30-round box magazine used by M-16s could also be fitted to the Ultimax 100 once two holes were drilled near the magazine lip. The Ultimax 100 was demonstrated with much bravado, with firers frequently letting off all 100 rounds in one impressive burst and sometimes firing it without its plastic buttstock, with the butt plate on the nose of the firer to underscore that the SAW's constant recoil principle produced very little recoil force.

The Ultimax 100 gave an SAF section of nine soldiers (reduced subsequently to seven soldiers) much improved firepower as the section had previously relied on heavy-barrel AR-15 rifles for sustained automatic fire. As such fire was limited by the 30-round box magazines, infantry sections armed with the purpose-designed SAW – essentially a light machine gun – saw their firepower boosted tremendously.

Despite success in tests and demonstrations, the Ultimax 100 did not enjoy a reputation for reliability. Mr Henry Cheong related that he and Mr Chia Mow Chick, Head of Weapons Development was observing a firepower demonstration by an infantry battalion at the live firing range of Sungei Gedong. They were on an observation tower and could see all the weapons of an infantry battalion from 84mm Carl Gustav anti-tank rounds being fired to 5.56mm rounds. The repeated stoppages of the Ultimax 100 caught their eyes. They could not understand why the weapon would stop after every few rounds. Upon the conclusion of the firepower demonstration they went to examine the Ultimax 100. They found the two steel pins that held up the aluminium magazine had enlarged the holes in the magazine. Rounds could not chamber properly when the magazine was not properly aligned. The solution would be to introduce a gauge to check on the magazines and to dispose of those magazines that were beyond the allowable tolerance. The reputation of



ST Kinetics' CIS50MG 12.7 heavy machine gun



ST Kinetics' families of low-velocity 40mm ammunition (left) and high-velocity 40mm ammunition (right)



a weapon could be irreparably damaged if the problems detected in the field were not addressed immediately, and the cause and solution made known to all users.

The Singapore-made infantry weapons that SAF soldiers were armed with each represented what former Chief of Defence Force, LG Winston Choo, described as a "quantum leap" in capability.

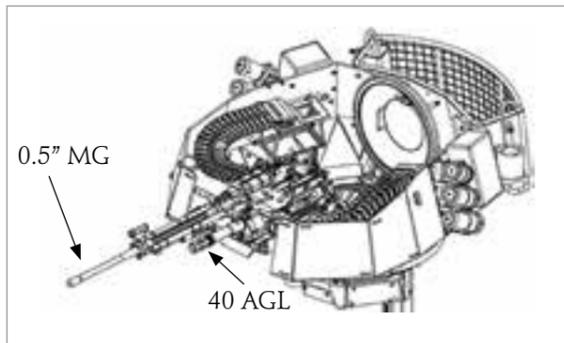
The CIS50MG 12.7mm heavy machine gun, CIS40 automatic grenade launcher (AGL) and the family of high- and low-velocity 40mm grenades designed and produced by CIS are, likewise, quantum leaps in infantry firepower.

The CIS50MG is a fifth lighter than the venerable Browning M2 0.5" machine gun it replaced and gives SAF troops a simpler, modular weapon that offers ease of use, operation and maintenance with better



Left & Right Feed of CIS50MG, with feed covers open

performance. What is more, it is designed with left and right feed, which gives weapon mounts added flexibility for twin machine gun configurations to maximise suppressive fire, or in pairing the machine gun with an AGL for added firepower during the assault.



Cupola platform with twin weapons concept (40mm automatic grenade launcher and 0.5" machine gun) for M113

Our ammunition designers have also worked hard to improve the effectiveness of the CIS50MG, with a special armour-piercing round called a Saboted Light Armour Penetrator designed to penetrate some 20mm of armour plate from more than a kilometre away.

It is not generally known that Singapore is the world leader in 40mm AGLs and produces possibly the widest range of ammunition types for this devastating crew-served weapon.



Saboted Light Armour Penetrator to defeat lightly armoured vehicle



At barrel exit



At 600mm from the barrel exit



At 2.2m from the barrel exit



ST Kinetics 40AGL MK2



Demonstration of Air Bursting Muniton System, exploding as a string of pearls (left), in front of window (centre) and beside an alley

Singapore's 40mm AGL team also scored a world's first when it designed the first Air Bursting Muniton System (ABMS) for standard and lightweight versions of the belt-fed automatic weapon. These programmable ABMS munitions are set by a magnetic coil when the individual grenades are fired. The grenades can thus maximise their lethality by exploding behind walls or windows, above roof tops, trenches or open hatches or as a "string of pearls" against troops in the open or behind cover.

Engineering Capability for Integrated Armament Development

CIS was fortunate to find some 300 young and daring engineers to drive armament development in its Engineering Department. The three critical success factors were, firstly, the availability of Singaporean engineering graduates willing to contribute to the build-up of Singapore's defence capabilities, secondly, then-CIS President Mr Lai Chun Loong who believed in nurturing defence engineers and lastly, Mr Lai's commitment to back his belief in talent development with the resources needed to trigger armament development projects. CIS allocated some 1% of the company's revenue to its Engineering Department, with weapon development

projects steered by an engineering leader, Mr Henry Cheong.

Mr Lee Chuen Fei and Mr Lee Kah Hoo were just two of the 300 engineers in the Engineering Department. From their recollections, readers can sense their passion and commitment to defence engineering. Also evident from their recollections is the exciting journey of discovery, the joy of successful product trials and learning from failures, which are par for the course during the creation of products that were beyond world-class.

Mr Lai had shared some on a smart phone. He was too modest to share on his achievements in growing CIS and later ST Kinetics under his leadership.

The unsung hero of armament engineers in Singapore is Mr Cheong. His ability to conceptualise engineering and operational issues in the products under development was unmatched by anyone in Singapore. His depth of knowledge and keenness to learn helped him forge deep and lasting friendships with the top armament engineers in the world. They would open their closely-guarded secrets to him because he had earned their trust. He led by example, daring to trust his engineering judgement and validate his ideas through extensive tests and evaluation, in weapon laboratories and during extensive field trials with defence engineers and weapons staff officers.

A unique capability of Mr Cheong was his understanding of the users and their requirements, many of which were unique to the SAF's operational requirements. He had learnt this from the various OR Departments of the UK MoD, the British Army, Royal Navy and RAF. It was Mr Cheong's innate ability to integrate operations and defence technology that differentiated him from other armament engineers.

Mr Cheong was also too modest to write

about his achievements but shared that the secret of the Engineering Department's success was due to the trust earned from his boss, Mr Lai. They were trusted to invest without having to write long papers of justification. Mr Cheong stated that despite the worry that Mr Lai had expressed on the Engineering Department's wish list ("Henry will bankrupt the company!" was a phrase Mr Lai had used occasionally to describe Mr Cheong's exploits), he did not pull back his support when development projects did not progress as planned.

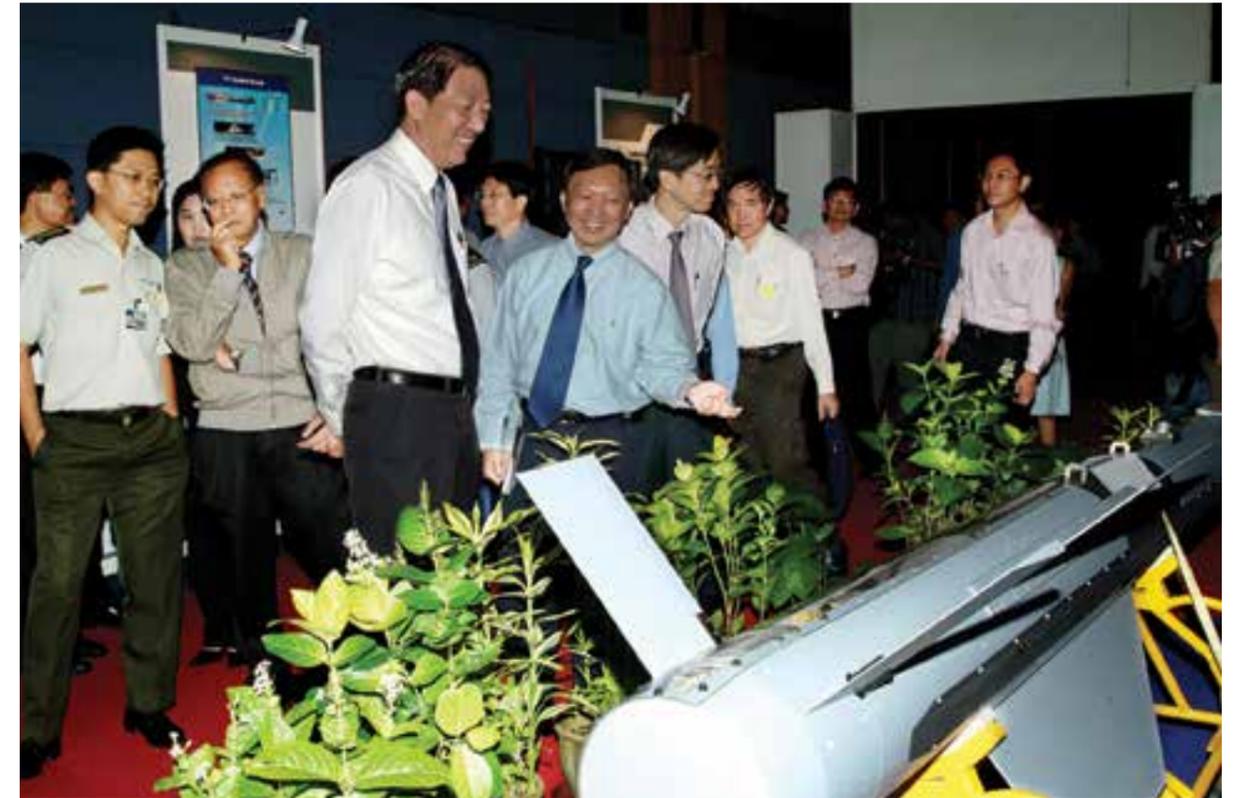
The Engineering Department of CIS has evolved into other forms with the reorganisation of the entities of ST Kinetics. The spirit of daring to dream and delighting users will continue with leaders who understand how to excite their staff to take on challenges and create opportunities to make Singapore a safer country.

Mr Cheong had earned the trust of the CIS Board and its President, as well as the leadership of ST Engineering, where much of Singapore's defence industrial capabilities reside. He had also earned the trust of the users of armaments produced by CIS, the officers and soldiers of the SAF.

A single word that would encapsulate the critical success factor of integrated armament development is Trust.

Postscript

Besides CIS, engineers and scientists elsewhere in the Singapore's Defence Technology Community (DTC) have also contributed substantially to the evolution of the precision weapon capabilities of the SAF over the years. Some of these have remained so classified that their full story cannot be told even as the DTC marks its 50th anniversary. Occasionally, we do get tantalising glimpses of the DTC's level of expertise in this domain. For instance, in 2004 DSO's TV-guided bomb was shown



Then Minister for Defence viewing the DSO's TV-guided bomb at the 3rd Generation SAF TechX Defence Science Exhibition, 2004

to the public for the first time at the 3rd Generation SAF TechX Defence Science Exhibition – some 20 years after the TV-guided bomb was developed as a technology demonstrator.

DEVELOPMENT OF 155MM ARTILLERY

The history of the Singapore Artillery can be traced back to the 1880s when the Singapore Volunteer Artillery (SVA) was first established in February 1888. It was absorbed under the SVC with the latter's formation in 1901. In the 1950s, this artillery branch under the SVC was set up as the Singapore Royal Artillery (Volunteer) and by the early 1960s, it was known as the 10 SVA.

Following Singapore's independence on 9th August 1965, the SVC was re-organised as the PDF and the 10 SVA was re-designated as 20 PDF (Artillery) which eventually became known as the 20th Battalion Singapore Artillery. Over the years, the SA evolved into four artillery units, each with its unique capabilities to serve specific roles and functions.

The Early Years with Artillery Weapon Systems

The SA operated mainly with mortar systems in the 1960s. The 120mm lightweight mortars from SOLTAM were acquired, and although heavy, they were intended to be man-portable by foot soldiers. As the SAF expanded from infantry battalions to the formation of infantry divisions and armoured brigades, the 120mm lightweight mortar was no longer able to meet the SAF's operational requirements. The Logistics Division thus sought to upgrade the mobility of these lightweight mortars to the 120mm standard mortar that could be towed using a Land Rover vehicle.

With the acquisition of the V-200 armoured personnel carrier in the early 1970s, the Logistics Division embarked on a project to mount the 120mm lightweight mortar onto the V-200 to enhance its mobility, and

reduce the effort needed to dig the ground to emplace the base plates. Testing proceeded well until the firing of the mounted mortar at high charge resulted in the V-200 engine breaking from its mounting, among other equipment failures. The development of the V-200 120mm mounted mortar was thus deemed a failure as the V-200 was unable to withstand the firing of the mortar at top charges. The limited range of the 120mm mortar was also assessed to be unacceptable.

Formative Years with Artillery Guns

The SAF needed longer range artillery guns with greater firepower but there were limited choices in the market in the early 1970s. A study was carried out by MAJ Lui Pao Chuen from the Logistics Division in December 1970 to evaluate the cost-effectiveness between the 105mm guns and the 155mm gun howitzers. While the 105mm guns were lighter and could achieve a higher rate of fire (three times faster), the 155mm guns offered greater target effectiveness and was concluded to be more cost-effective.

A team of logistics and artillery officers visited the UK, Israel and Sweden to evaluate the 155mm towed guns and the self-propelled (SP) guns, which included the FH70 towed howitzer (UK), the SOLTAM M68 towed howitzer (Israel) and the SP155 self-propelled howitzer (Sweden). The US was not prepared to sell their M109 SP gun, but offered the



M68 Gun of the Singapore Artillery

M110 203mm SP gun which was not suitable for the SAF due to its vast size and weight.

The FH70, M68 gun and SP155 had both strong points and shortcomings.

The FH70 towed howitzer was still in a conceptual stage then, and being a tri-nation project, the requirements of the three member nations would take precedence over Singapore's requirements. As for the SP155, while it was a state-of-art gun¹ then, it was not in production and came with an exorbitant price tag of \$4.5 million. In addition, Dr Goh Keng Swee, then Minister for Defence, expressed that technical know-how wise, the SAF then was also not ready to operate the sophisticated SP155 gun.

The M68 gun was eventually acquired for the SA to develop their doctrinal and operational procedures. Although the contract was signed in 1971, the equipping of the SA's ORBAT could not be met in time due to the failure of SOLTAM to meet the contract delivery. While awaiting the delivery of the M68 guns, the M114 155mm gun howitzer was acquired through an opportunistic buy². These M114 guns were refurbished at the Ordnance Maintenance Base and became the first operational artillery gun in the SAF in 1974.

The first unit of M68 guns was delivered in 1973. However, not long after delivery, the serviceability level of the M68 plummeted to a low of 20%. We found that we had no understanding of the gun design, and

¹ The SP155 had an exceptionally high rate of fire. A three-man crew could operate the system, which could fire 15 rounds in 45 seconds, with one round loaded in the gun, and two seven-round clips in the magazine. It fired the BOFORS fixed-ammunition that had a weight of 47kg and a tactical range of 28km.

² The M114 gun howitzers were bought at scrap metal value.

³ The rifling of the M68 gun was 33 calibres in length, while that of the M71 gun was 39 calibres which gave it a much longer range. (Note: The internal diameter of the gun tube is referred to as the calibre. Hence, 33 calibres is 33 times of 155mm.)

⁴ Sealing of gas generated during firing.

had no technical manuals or maintenance instructions to refer to. A team of engineers and technicians was sent to SOLTAM to understand the design and establish the maintenance regime required. Based on the Army's operational and training doctrines, the first set of its operation and maintenance manuals for this gun was developed under the leadership of LTA Teo Ming Kian, who was a military engineer with the Logistics Division then.



M114 Gun of the Singapore Artillery

FH88 - First Local Gun Design and Development

Following the phasing in of the M68 guns, the M71 guns (a longer range derivative³ of the M68 gun) were bought by the SAF. Both guns were plagued with low reliability, obturation⁴ and hydraulic leakage problems. Mr Teo Ming Kian recalled, *"While trying to solve the serviceability problem, I began to think about how to produce some of the components locally. The parts that were supplied by SOLTAM were very expensive. Worse still, they were not readily available. This was probably when the idea of local production was first conceived, not so much for self-sufficiency, but to ensure readiness."* The recurrent problems of the M68 and M71 guns prompted the SA to source for more advanced systems in the late 1970s and early 1980s.

A feasibility study on the local development of a 155mm gun, based on our experience with the M68 and M71 guns, was carried out by

ODE in 1977. The study concluded that *“the best approach to execute local production was to obtain a licence and technical data package”*. This would shorten the long lead time to formulate the design specifications and design the gun from scratch, and also reduce investment risk and assure project success. The management of ODE was, however, reluctant to take the business risk of producing the 155mm gun.

It was only in 1982 that the idea of a locally designed and produced 155mm gun was supported by Mr Loh Chuk Yam when he took over as the General Manager of ODE. Two key considerations that might have led to the change in direction were the large number of guns that the SAF needed and eventual business prospect for the company.

The SA was resolute in looking for a more reliable gun with a higher rate of fire that could be operated by a smaller crew. From an initial list of possible candidates, namely, the FH70 (UK), M198 (US), Bofors FH77B (Sweden), SOLTAM M839P (Israel) and Giat TR155 (France), only the FH77B and M839P were shortlisted as prospective candidates that could meet the Singapore Artillery’s requirement. Three options to the acquisition approach were also considered: to proceed with an off-the-shelf buy, to secure licensed production with a technical data package from the original equipment manufacturer, or to indigenously design and build our own gun.

An off-the-shelf buy would be relatively straightforward and would carry the lowest risk with the shortest delivery schedule. The production know-how of the guns would reside with the suppliers. On the other hand, local production under licence was becoming a common strategy adopted by most developing countries for the purchase of weapon systems from overseas suppliers. This approach would entail minimal development risks and some transfer of technical know-how to produce parts of the gun. There would be limited expertise build-up in the local design and

development of guns. The third option was for MINDEF to contract ODE to locally design, develop and produce a 155mm gun with improved features. This would come with the highest risk given that ODE had, up to that point in time, produced only small and medium calibre weapons and mortars. For ODE to commit to producing a 155mm gun with improved features over the in-service guns at a lower cost, and within the same timescale as licensed production was an audacious goal. However, it was a crucial opportunity for our local defence industries to build up local design and development capabilities of weapon systems. It was also a significant stepping stone for MINDEF and the local defence industries, to work towards the much-desired self-reliance in providing support and depot maintenance capability for weapon systems.

Of the three options, the Army fought for the lowest-risk off-the-shelf buy. It was also the most expedient route to build up the Singapore Artillery’s ORBAT as the operator training and logistical support that were in place with the supplier could be easily adapted to suit the Army’s requirements. The Army was not supportive of a locally-designed gun as ODE’s proposed gun without a burst firing capability fell short of its requirement. The SA, too, had no confidence in this promise of a conceptual gun.

From the perspective of the Logistics Division, Mr Teo Ming Kian strongly advocated the third option. He saw it as an excellent opportunity to improve on the design of the existing guns while building up local production and maintenance capabilities. At the strategic level, in a period of tension, the SAF would have greater assurance of access to the necessary spares and maintenance support. The acquisition cost was also the lowest of these options considered.

Evaluation trials of overseas 155mm guns were conducted locally. The Army was keener

than ever in acquiring the FH77B guns from Bofors arising from encouraging results of the demonstration trials. It became increasingly difficult to convince the Army to go with the local development option. Mr Teo Ming Kian, then Director of Logistics Division, recalled the eventful meeting in January 1983 that Mr Goh Chok Tong, then Minister for Defence, had with the Chief of General Staff, MG Winston Choo, the 2PS, Mr Philip Yeo, and himself. This was after the MINDEF HQ meeting where the Army registered great resistance to the local design and production of a 155mm gun, citing bad experiences that the Army had to “live with” such as with the SAR80 rifles⁵ that were produced by the CIS. *“I could still remember the atmosphere in the room at Tanglin Road, called “the White House”. It was at that meeting that the Minister for Defence laid the responsibility of the project on my shoulders,”* Mr Teo Ming Kian recalled.

With the encouragement and support from Mr Philip Yeo, Mr Teo Ming Kian went to MINDEF HQ to seek approval for the local development and production of the 155mm gun howitzers by ODE. The approval was obtained and a contract was signed with ODE for the local development and production of the 155mm towed gun howitzers which had to be reliable, be equipped with cross-country mobility, burst-rate firing capabilities and labour-saving features for easy deployment of the gun.

Overcoming the Odds

Design and development work took off at full steam in ODE with close collaboration between the engineers from the Materials Management Organisation⁶ (MMO) and ODE. ODE had to rapidly assemble its best team

⁵The “SAR-80” rifle was unreliable and a setback, with long downtime due to poor design and poor maintainability.

⁶In April 1983, the separation of engineering and logistic functions in the Logistics Division led to the formation of the Materials Management Organisation (MMO) and G4, Army respectively.

of designers and test engineers, build up its design facilities and set up its manufacturing facilities concurrently. The Army officers shared with the engineering team their operational and maintenance experiences with the M68 and M71 guns. Sub-systems that were critical to safety, such as the gun barrel, breech mechanism and recoil system, were identified and their designs and sub-system qualification test plans thoroughly scrutinised. Sub-systems that were crucial to the gun meeting key performance specifications, such as the auxiliary power unit and ammunition handling system (rammer and primer loading mechanisms) were constantly reviewed through numerous test-and-fix cycles. Structural components were initially thought to be straightforward mechanical systems given established design and manufacturing codes. But, as it turned out, fatigue failures due to the high-impulse loads and cyclical loads provided tremendous lessons to the team in what constituted good designs (in terms of functionality, reliability and maintainability), while ensuring consistency and cost-efficiency.

ODE senior management also met up with the design teams regularly to provide strategic guidance and monitor the overall progress of the project. Where it made sense to collaborate with other market players instead of an indigenous design and in-house production, the team was given leeway to do so. In most instances, the ODE team would explore if it made sense to produce parts under licence or to secure sufficient local content so as to build up its engineering capabilities for local depot-level maintenance. Close co-operation with overseas contractors was established for the development of key sub-systems of the gun, such as the auxiliary power unit and the flick rammer system.

While design work was ongoing, the technical team and the Army users worked out the qualification and acceptance test plans. Sub-system testing and in-factory tests were carried out where possible to root out early failures and increase confidence before



FH88 Stealing the Thunder from the Big Guns

elaborate field tests and live firing of the gun. An overseas range was secured for the testing of the engineering prototypes through political channels. This search for an overseas firing range was not easy, but for the first time, the SA was able to fire at ranges beyond 8km from its 155mm guns.

The design approach undertaken by ODE was to first qualify a basic gun and then look into add-ons and modifications to resolve performance and reliability requirements. While the addition of features could be more readily accommodated, the design team at ODE learnt through a painful process that reliability must be planned for and designed into the weapon system right from the start.

Within two years from the decision made to proceed with the local design and production of an artillery gun, two prototypes were completed. The first local firing was carried out in October 1984, and the first overseas firing test was conducted in December 1984. Over the next two years, the project team spent most of the time in overseas firing ranges to troubleshoot and qualify the gun performance in range, accuracy and mobility, and validate its structural integrity.

Being the first 155mm gun designed by ODE, the designers took a conservative approach and opted for large safety factors when little was known of the dynamic performance of critical parts. The prototype, with all the add-on features, was too heavy and its arc of

fire was too small. The requirements stated previously for weight and traverse range were 12 tonnes and 60° respectively and both requirements were deemed critical to the SA. Several discussions were held with the Chief of Artillery and senior representatives from ODE and MMO to work out possible solutions, and to decide on the trade-offs. Ms Ho Ching, then Senior Director of MMO, was instrumental in fostering the tripartite working relationship, and with the active participation of Army senior representatives in the decision-making process, the final configuration of the gun was more readily accepted by the SA. This milestone was remembered by many in the project team as a significant breakthrough in the working relationship among the three parties.

The requirement of a burst-rate firing capability meant that the ammunition-loading (specifically, the projectile and primer loading) had to be automated. A flick rammer and an automatic primer feeding mechanism were key features of ODE's gun that enabled its burst-rate firing capability. ODE, MMO and the SA made significant contributions in terms of engineering effort and providing user input to qualify and fine-tune the flick rammer that was designed by an Austrian sub-contractor. Our local gun became the first gun howitzer that was fielded with a flick rammer.

By early 1987, the final prototype gun was successfully tested after close to four years of development and rigorous testing. The gun, at 12.9 tonnes, although somewhat heavy for a 39-calibre gun, was eventually delivered to the Army user. It had excellent deployment features and firing accuracy. A crew of six men could easily deploy the gun in less than one minute, which was the fastest deployment time achievable by any towed howitzer then. The gun was designated as the FH88 and the first battalion of 18 FH88 guns was commissioned in 1988.

Total Systems Approach in Project Management

The project team comprising MINDEF and ODE personnel concentrated most of its effort on testing and meeting the performance of the gun during the development phase. The logistic and performance requirements such as reliability, availability and maintainability (RAM) were only looked into much later in the development and production phases.

In 1986, MMO merged with Special Projects Organisation (SPO) to form the Defence Materials Organisation (DMO). Under the leadership of LTC Wesley D'aranjo then Deputy Director (Armaments/Land Systems), the project team took a total systems approach in the management of this project. This was subsequently institutionalised and documented in MINDEF's Life Cycle Management (LCM) Manual, which became MINDEF's way of doing business⁷.

Failures and design reviews were systematically tracked and relentlessly followed through till every issue was resolved. Strict discipline in project management beyond the development and production of the guns was enforced to ensure the delivery of a total operational capability. Acquisition of ancillary equipment such as trucks, artillery directors, collimators, camouflage nets and muzzle velocity radars, which were essential to the fighting capability of the gun battalions, was expedited to catch up with the delivery schedule of the guns.

This project pioneered the implementation of an Integrated Logistics Support (ILS) methodology in the Army to holistically include requirements of training, documentation, support and test equipment. This has since become a standard methodology for the acquisition of all weapon systems and equipment.

⁷The LCM manual was recently reviewed and designated as the Defence Capability Management Manual.

Teamwork

The FH88 gun development was an excellent example of MINDEF, the SAF and our local defence industry venturing into a programme with moderately high development risks, and despite the odds. The tripartite effort was not without challenges, but these were eventually solved with the determination of MINDEF leadership and the perseverance of the project team that saw to its successful completion. MINDEF engineers participated in the design process, as well as qualification tests of the gun. A dedicated project trial team from HQ SA was fully committed to test and evaluate the prototype, carrying out trials at unearthly hours to meet the tight project schedule. The deep involvement of such a team facilitated timely feedback and important improvements in the human factor engineering aspects of the gun, while allowing the SA to concurrently formulate its operational and training drills. The defence engineers from DMO and DSO brought along their engineering expertise in ILS methodology, RAM assessments and ballistic range table generation to the project.

Follow-On Gun Developments

With the technical know-how and the expertise built up from the successful development of the FH88 gun, ODE was more confident and ready to embark on new gun developments. The company took on the upgrade of the M71 gun to automate the operations of the gun and resolve reliability issues with its hydraulic and pneumatic systems. This cut down the number of men required to deploy the gun from 12 to 8. The upgraded gun was designated to the M71S and fielded in the SA in 1993.

FH2000 - A Bigger and Longer Gun

Following the commissioning of the FH88 in 1988, the SA sought approval for the acquisition of more 155mm guns to replace the in-service M71 guns. MINDEF deliberated



FH2000 155mm Gun Howitzer in the firing position

if the acquisition should be for more FH88 or for a longer calibre gun. From an operational perspective, a longer-calibre gun would give it a longer maximum range, providing the artillery with a greater stand-off distance. From a technological point, the development of a longer calibre 155mm gun was in line with the development of artillery weapon design houses to provide longer ranges to 155mm artillery systems, by way of extended range ammunition and longer barrels. In view of ODE's capability to develop and produce the FH88 guns, and for reasons of interoperability and commonality of spares with FH88, ODE was engaged to develop and supply the new 155mm, 52-calibre guns. Unlike the early days of the FH88 development, this time, the proponents pushing for local development of the longer range 155mm gun were from the Army.

In May 1995, the SA commissioned its first

battalion of FH2000 guns which was the first 155mm gun howitzer with a 52-calibre barrel in the world to be fielded into operational service. The longer barrel of the FH2000 gun increased its maximum range to 40km with extended range ammunition, 10km above that of the FH88 gun. Relative to the FH88 gun, aside from the expected increase in range, the FH2000 gun was more reliable



FH2000 155mm 52-calibre Gun Howitzer

and easier to maintain, with no increase in weight. Requirements such as commonality of parts to the FH88 guns, and compatibility with existing in-service equipment such as towing vehicles, ammunition and support equipment were specified upfront. The gun was also equipped with an improved electronic system using programmable logic circuits that were more reliable, and modular sub-systems for easy maintenance.

Since its introduction into service, the FH2000 gun has been well-received by the soldiers. It was easy to use because many functions had been automated. For the maintenance technicians, the modular design allowed for fast and easy servicing and maintenance.

A Dark Moment, A New Dawn

On 9th March 1997, a 155mm high-explosive round exploded prematurely, killing two and injuring 12. The artillery accident happened in Waiouru, New Zealand, where 23SA was training. When news of the artillery accident reached Singapore, the technical teams in DMO and ODE were quickly activated to investigate and establish the root cause of the accident. From the fault tree analysis of the gun and ammunition, all plausible causes were investigated. Within four days, the first sign of evidence pointing to a faulty fuse surfaced. From x-rays of the lot of fuses used in the artillery exercise, a pre-armed fuse was discovered.



Damaged FH2000 Gun from an in-bore explosion

Safety Management and a Safety Journey

The lessons learnt were painful but the resolve of the engineers and senior management in MINDEF and the SAF was to institutionalise the learning so that such an accident would never happen again. From that dark moment of tragedy, the seed of a safety culture was sown. With unwavering support from senior management in MINDEF, the defence engineers left no stone unturned in the years that followed as they systematically reviewed the design safety of weapon and ammunition systems in the SAF inventory. They reviewed the processes and methodologies of qualification and acceptance of weapon and ammunition systems. They strengthened the management of contractors and sub-contractors, and surveillance management of ammunition systems. They holistically reviewed the training and operational drills with the Army and adopted a system safety approach to ensure a high level of safety assurance in the operations and training with Army weapon systems for our soldiers. It was a defining moment for the defence engineers and the Army, as they collectively embraced the learning that *"armament safety is written in blood"*. There was a unanimous acceptance of the onerous safety responsibilities and the need for clear accountability for the safety of every agency in the value chain. This was the beginning of the system safety journey in MINDEF.

PRIMUS - A New Era of Fighting Capability

In the early 1990s, the Army conceived the requirement for a weapon system that combined the range, firepower and accuracy of an artillery system with the ability to keep pace with the high tempo of armoured operations. The FH88 and FH2000 towed guns had neither the mobility to keep pace with the armoured forces nor the protection required to survive the threat environment. A

The 155mm Gun Howitzer Chamber Explosion on 9th March 1997 in New Zealand

MINDEF's release on 28th June 1997 on the investigation outcome and mitigation measures taken to ensure soldier safety, shortly after the 155mm Gun Howitzer Chamber Explosion in New Zealand on 9th March 1997.

A 155mm SA round exploded in the barrel of a FH2000 gun howitzer on Sunday, 9th March 1997 in Waiouru, New Zealand, during a live firing exercise conducted by the 23rd Battalion, SA. The incident resulted in the death of two full-time national servicemen, Third Sergeant Ronnie Tan Han Chong and Lance Corporal Low Yin Tit. Another 12 servicemen, including a Staff Sergeant from the New Zealand Defence Force, were injured in the incident.

The Ministry of Defence (MINDEF) convened a Committee of Inquiry on 17th March to investigate the circumstances leading to the incident. The Committee was chaired by Mr Tan Gee Paw, Permanent Secretary (Environment). The other five members of the Committee included Mr Andrew Renton-Green, a senior official from the New Zealand Ministry of Defence, and representatives from the Ministry of Health, Legal Services of MINDEF, and the Singapore Armed Forces (SAF).

On 2nd May, the Committee submitted its findings and recommendations to MINDEF. The Committee concluded that the correct procedures had been strictly followed by the Singapore Artillery unit involved, and there was no human error by any member of the unit. There was also no breach of any SAF training safety regulations.

The Committee concluded that the most

probable cause of the incident was a defective fuse that was attached to the 155mm shell which was loaded into the gun howitzer. The defective fuse resulted in the premature explosion. After the incident, the lot of fuses from which the defective fuse came was X-rayed. 1.3% of the fuses were found to be defective.

This defective lot of fuses was supplied by the Chartered Ammunition Industries (CAI) to MINDEF under an agreement in 1992. CAI was to supply fuses manufactured according to internationally accepted military specifications. These military specifications require thorough inspections and other quality control measures during and after the manufacturing process to eliminate all defects in the fuses.

CAI, in turn, contracted with a U.S. company, Island Ordnance Systems (IOS), for the supply of these fuses. Without the knowledge of CAI, IOS obtained the fuses from Xian Dong Fang Machinery Factory in the People's Republic of China (PRC). In October 1994, CAI discovered that the fuses were manufactured at the factory in the PRC rather than in the USA. However, CAI did not notify MINDEF of this discovery. MINDEF only became aware that these fuses were manufactured in the PRC during the Committee of Inquiry proceedings in March.

When the fuses were delivered to CAI, IOS issued a Certificate of Compliance and a Certificate of Conformance to confirm that the required military specifications had been met. Sample testing of the fuses was also conducted by CAI during which no defective fuses were found. Based on these Certificates, MINDEF accepted the fuses from CAI.

MINDEF is responsible for ensuring that

all types of ammunition and fuses used in the SAF are safe. MINDEF does so by conducting acceptance testing of ammunition and fuses either by itself or by reliable contractors. In this case, MINDEF had engaged CAI to provide the SAF with the fuses. In particular, CAI agreed to witness the acceptance tests for the fuses, on behalf of MINDEF. However, CAI did not witness all the acceptance tests. CAI also did not check whether the factory in the PRC was able to manufacture the fuses according to the required military specifications.

To prevent defective fuses from being introduced into the SAF inventory again in future, MINDEF will completely revamp the current acceptance process. MINDEF has also ceased using all types of ammunition and fuses from IOS. MINDEF will also not accept ammunition and fuses manufactured by Xian Dong Fang Machinery Factory.

MINDEF will continue to use 155mm fuses of this type which have been made by a different manufacturer. As an added precaution, all such fuses will be X-rayed. With these precautions in place, the SAF resumed live firing with the 155mm guns in May.

Source: http://www.mindef.gov.sg:80/content/imindef/press_room/official_releases/nr/1997/jun/28jun97_nr.html

detailed market survey of both turreted and non-turreted self-propelled gun-howitzers (SPHs) was carried out (which included the US Paladin M109A6 and German PzH2000) but none of the systems met the demands of the SAF's tactical environment without substantial customisation; thus, a decision was made to develop the 155mm SPH locally.

Following the development of the FH88 and



PRIMUS 155mm Self-Propelled Gun-Howitzer

FH2000 towed guns, the SPH was another step towards building up a local capability in ordnance engineering and development. It involved the integration of on-board computers and innovative automation to a turreted 155mm gun on a chassis. The original intent was to use the chassis of the Bionix infantry fighting vehicle from ST Kinetics. However, with the need for massive engineering changes to customise the Bionix chassis to integrate the SPH turret, the decision was made to acquire the modified M109 chassis from United Defence instead. Thus, the SPH was designed and built by integrating local and foreign sub-systems, with significant leverage on electronics in its fire control and drive systems. The first SPH, PRIMUS, was rolled out and commissioned by then Minister for Defence, Mr Teo Chee Hean in November 2003.

Given its greater responsiveness and flexibility, and compared to the FH88 and FH2000 guns, the PRIMUS represented a quantum leap in the Army firepower capability. Not only was



PEGASUS 155mm Lightweight Howitzer

it able to respond with firepower support to the frontline much faster than the field howitzers, it was able to do so without much ground preparation. Then CO of 21SA, MAJ Alex Tan said, *“The PRIMUS was at the forefront in empowering our NSF commanders with greater autonomy and responsibilities given to them. This is due to the PRIMUS’ higher system complexity and fighting capability, enabling more than 50% reduction in the crew size compared to the FHs. The operationalisation journey of the PRIMUS within the Artillery formation was daunting given the steep learning curve but our NSFs stepped up to the plate and carried themselves commendably.”*

PEGASUS – A Lightweight Gun

In the late 1980s, the SAF acquired a fleet of 105mm Light Guns from GIAT Industries to provide fire support for our heli-borne forces. By 1994, the Army had reviewed the roles of the heli-borne artillery and debated on the merits of having 105mm guns versus 155mm guns. The 155mm guns emerged as the preferred choice in view of its superiority in

munitions effects and range, and the desire to have a common calibre for logistics simplicity.

The key challenge to move from a conventional 155mm gun to a heli-portable 155mm gun was the significant weight reduction required – at less than half that of the FH88 gun – while being able to withstand the same firing loads. This was to be achieved with the use of lightweight materials such as aluminium and titanium. Although this might sound similar to the design approach in the aerospace industries but when used in gun structures, the high-impulse load was a different order of magnitude. The weight reduction efforts had to be finely balanced with the structural strength required to withstand the recoil forces during firing and the aerodynamic loading when heli-lifted.

In 1996, the SAF, DMO and ODE embarked on a market survey to explore the lightweight 155mm guns from Lockheed Martin, Vickers Shipbuilding and Engineering Limited (VSEL), and Royal Ordnance. The respective guns

had been under development for some time and were in competition to replace the M198 155mm towed gun used by the US Marines and Army.

The long recoil design of the ultra-lightweight field howitzer from VSEL⁸ was assessed to be more mature in its design and able to meet our requirement. ODE and VSEL were working towards an agreement for the supply of the titanium structure but the collaboration fell through, and in 1998, ODE decided to proceed with an indigenous design of the lightweight 155mm gun.

The Army took the opportunity to review their requirements and included an Auxiliary Power Unit to enable the gun to have limited mobility capability. The revised contract was signed with ODE in 1999. The use of aluminium and titanium for the design and manufacturing of the lightweight 155mm gun was a challenge for ODE. Under a weapon offset programme, the assistance of Boeing was sought to provide training for titanium design, welding and fabrication. Photonics of Austria was commissioned to design and produce the sighting system and the sight mount. It took several rounds of Development Test & Evaluation (DT&E) firings and numerous design changes before qualification trials were eventually completed. DT&E and Operational Test & Evaluation (OT&E) trials were completed in 2004 with the first gun delivered in early 2005. This new 155mm artillery gun, officially named the ‘Singapore Light Weight Howitzer (SLWH) Pegasus’, was commissioned by then Minister for Defence, Mr Teo Chee Hean on 28th October 2005. The Pegasus became the world’s first heli-portable 155mm lightweight howitzer with a self-propelled capability.

⁸The ultra-lightweight developmental prototype from VSEL was subsequently developed for the US Army and designated as the M777 Howitzer.

DEVELOPMENT OF ARMoured FIGHTING VEHICLES

Even without our own national car, Singapore's defence industry has led several homegrown projects to design and manufacture armoured fighting vehicles (AFVs) for the SAF.

Singapore-made armour is now the dominant force in the SAF's ORBAT, not just in numbers but the diversity of roles. The requirement for tracked and wheeled light armour of around 30 tonnes has been fulfilled by Singaporean expertise through the defence company, Singapore Technologies Kinetics (ST Kinetics, earlier known as SAE).

Over the years, ST Kinetics has led projects to upgrade AMX-13 light tanks, M113 armoured personnel carriers (APCs), V-200 armoured cars and developed home-grown armoured vehicles such as the Bionix, Terrex, Bronco and Primus 155mm self-propelled howitzer. The ST Kinetics stable of AFVs continues to grow.

One of ST Kinetics's latest projects, the New AFV for the Singapore Army, was started jointly with DSTA in 2006 and has reached final prototype stage. The New AFV, which is built to optimise the use of integrated fires between combat platforms and fast, secure exchanges of battlefield information, represents a quantum leap in capability from the M113 Ultra APCs it will replace from 2019.

Such expertise was hard won. The track record of Singapore's defence industry shows a steep growth trajectory in the past 50 years. It was a tough slog for defence engineers and scientists tasked to sharpen the combat capability of the SAF's armoured vehicles. This chapter traces key milestones that led to the capability jumps from the provision of basic vehicle maintenance which matured to depot level

maintenance before advancing to the ability to upgrade armour.

The leap to the next S-curve or higher level of capability was achieved with projects to develop the Bionix infantry fighting vehicle and the Bronco all-terrain tracked carrier. These 1990s-era projects gave Singapore the expertise and experience to design, build and integrate automatic weapons and guided munitions aboard armoured platforms unique to Singapore.



The prototype New Armoured Fighting Vehicle undergoing mobility trials

The groundwork was laid in the late 1960s when the SAF acquired its first armoured cars the V-200 Commando, and introduced the AMX-13 light tank as its first tank.

Armoured vehicles had been fielded successfully during the Battle for Singapore in World War II (WWII), with the Japanese proving the value of armour during the war of manoeuvre that led to the capture of Singapore from the British.

Tanks in the Malaya Campaign

During WWII, the British and Japanese both realised that the supposedly impenetrable jungle terrain in Malaya was actually passable to light and medium armour if they kept on trunk roads and unpaved plantation tracks that were on firm, dry ground.

The Japanese invasion force that landed in

Malaya therefore used light and medium tanks and small armoured tracked carriers like tankettes to spearhead its advance down the Malay Peninsula towards Singapore. Facing them were British armoured cars like the Lanchester, Marmon Herrington and the Indian Pattern, along with Bren gun carriers – open-topped and lightly armoured tracked carriers.

In his biography, *The War in Malaya*, LG Arthur Percival, the British general tasked with defending Singapore, touched on the value of tanks. The general recalled how one of the last convoys of reinforcements (the ships arrived two weeks before Singapore fell) included the only tanks to serve in the Malaya campaign on the British side. These were Vickers light tanks, whose heaviest armament was a 0.5" machine gun.

"In the same convoy as this division arrived a light tank squadron from India. They were the only tanks ever to reach Malaya on our side. The tanks themselves, I fancy, had been collected from various training establishments and the squadron hastily formed. When they reached Singapore, some of them had to be put straight into ordnance workshops before they were fit to take the road. Some never did take the road.

An armoured brigade was due to arrive in the Far East early in March. When asked for my views on the destination of this brigade I recommended that the destination of one Cruiser regiment at least should be left in abeyance until nearer the time of arrival, as I felt that it might prove extremely valuable but that it was too early as yet to say whether it would be possible to bring it to Singapore."

Light tanks could be employed similar to the assault gun concept pioneered by the Germans during WWII, accompanying the infantry as a mobile gun to take out hard targets and to provide covering fire for the assault.

Procurement of Armoured Fighting Vehicle

The 1966 plan for the SAF's ORBAT of 12 battalions included two reconnaissance battalions. These two battalions would be equipped with the most sophisticated and lethal weapon system, the armoured fighting vehicle. This fighting unit would have the following operational elements: reconnaissance, commando, armour and engineering. The following armoured fighting vehicles would be required:

- Armoured personnel carriers
- Armoured cars with 90mm guns
- 81mm mortar carrier

The General Staff Division conducted in 1966 a study of armoured cars under production in different countries and shortlisted the following vehicles for further evaluation:

- Commander, Commando cars Bauer Ordnance (USA)
- Commando V-100 Cadillac Gage (USA)
- Henschel HWR-42 Rheinstahl Henschel AG (Germany)

The following vehicles were among those considered, and rejected due to low power-to-weight ratio and the lack of swimming capability:

- Mowag (Switzerland)
- Saladin (UK)
- Saracen (UK)

Cadillac Gage and Rheinstahl responded to a technical questionnaire on the capabilities of their vehicles in early 1967. On completion of the comparative study, the General Staff Division asked Director Logistics to request that Cadillac Gage send the Commando V-100 to Singapore for demonstration and field trials.

The Israeli advisors came to Singapore in 1967 to study and propose the build-up of our two

rece battalions. At that time, MID considered tanks to be a politically sensitive weapon system and did not consider their purchase. The Israeli advisors were of the opinion that the tank must be a central piece in the ideal model of the armoured forces where tanks were used to take enemy positions head on. The build-up of the armoured forces for the SAF would begin with armoured cars for the development of armour professionals, who could master the operation of tanks rapidly, once approval for their acquisition was given. A company of tanks would then be incorporated into the rece battalions, and later to consolidate the tanks into a tank battalion within an armoured brigade.

The Israeli advisors assessed the terrain, vegetation and climate of our area and concluded similarly that wheeled armoured vehicles would be suitable for our rece battalions. They proposed to bring in the French AML to Singapore for evaluation as well, in addition to the V-100.



The V-100 undergoing mobility trials, circa 1967

The conclusion of the evaluation was that the Commando V-100, which had seen action in South Vietnam, was superior to the French AML. It proved to be exceptionally mobile for a wheeled vehicle and it had a swimming capability which was demonstrated in a swim from Seletar to Pulau Tekong. The mobility and swimming demonstrations were highly successful and the audience was impressed.

A recommendation was then made to acquire the V-100 provided the manufacturer could upgrade the vehicle to meet the following operational requirements:

- A gun that would defeat thick steel at 800m
- A gun that would defeat armoured personnel carriers
- Infantry section to be able to observe and fire from inside the vehicle

The protection of the crew from 7.62mm armour piercing rounds had already been specified by the Israeli advisors in an earlier evaluation. The swimming capability was considered to be a critical requirement.

The first two requirements would need the development of a 90mm gun turret and a two-man 20mm gun turret respectively to be carried by the V-100. As Cadillac Gage was a specialist for turret controls – nearly all US Army tanks were fitted with Cadillac Gage turret controls – their engineers would have no problem designing turrets for the 90mm and 20mm guns. But, as these turrets had yet to be developed, they would need time for product development and testing.

The hull of the V-100 was designed to defeat 7.62mm ball rounds. The XAR-30 armour plates that were used to manufacture the hull were ¼" thick. To meet the operational requirement for armour protection against 7.62mm AP rounds, the thickness of the armour plates would need to be increased.

XAR-30 Armour Plate Testing

To verify that the thicker XAR-30 armour would defeat 7.62mm AP rounds, sample armour plates were sent to Singapore for testing. After checking for physical characteristics, like Brinell hardness of the steel, functional tests were performed at the SAFTI 25m range. The velocity of the bullet at 25m would be about the same when it left the rifle's muzzle, the highest velocity of the bullet.

Two-inch squares were drawn on the 18x18" test plate fitted on a stand which would allow the inclination of the test plate to be varied. The test was to determine the protection against different types of small arms ammunition. The testing officer rested his rifle on a sand bag at the firing point, and tried to get as tight a grouping as possible to simulate the case of multiple hits on the same point of the armour.

It was found that ball rounds with lead-filled bullets would be smashed flat like a postage stamp on the surface of the test plate. Armour piercing rounds with a tungsten core would bounce off the armour at various angles of inclination. The worst case for the armour would be at 90-degree inclination with the bullet striking perpendicular to the test plate. It was found that the tungsten core would gouge out bits of armour steel but did not penetrate the plate. There was also no spalling at the rear of the test plate.

After each round, the test plate was examined and the position of the round marked with paint. Half way through the firing test it was discovered that the can of paint was empty. The testing officer thought it was strange as the can was almost full when the last round was marked. A closer look at the can showed that the tungsten core of the last bullet had penetrated it. The testing officer reported that when he saw the hole in the paint can, a shiver went down his spine. The tungsten core had missed his head by two feet!

To minimise the risk of ricochet, the testing could be done at 100m range but the velocity of the bullet would not be close to the maximum. A decision was thus made to continue firing at the 25m range but with all non-testing personnel away at a safe distance. The testing team would fire the rifle remotely with a string tied to the trigger from a protected position. The testing took twice as long because of these safety measures.

On completion of the firing tests, the testing team could certify that the thicker XAR-30 sample had met the specifications for protection against the 7.62mm AP rounds. The hardness of the armour plate was critical to its protective ability. The welding of armour plates could create weakness, and technology and skills were needed to maintain the integrity of the monocoque hull of the armoured vehicle.

Years later, when testing the aluminium armour of the M113, it was learnt that the way aluminium armour defeated AP rounds was different from that of steel armour. The defeat mechanism of aluminium armour was absorption. The tungsten core of the AP round would penetrate the front of the armour plate, but the resistance of the material would slow it down and stop it before it could exit the rear face of the armour.

Development of the Commando V-200

The enhanced heavier hull and turret would be too heavy for the axles of the V-100, which now needed a capacity of five tons, up from 2.5 tons, thus adding more weight. The operational requirement for a 12" longer body and a wheelbase broader by 5" drove the maximum gross vehicle weight up from 16,250lb to 23,000lb. A new vehicle, the V-200, would need to be developed as the V-100 could not be stretched to meet all these requirements.

The V-200 was conceived to be a basic vehicle with outstanding cross-country mobility and swimming capability. The vehicle could be configured for different roles with minimal changes to the internal arrangement and no change to the components of the basic vehicle. As the mobility of the V-100 had been tested and found to be outstanding, MID decided to use the mobility of the V-100 as the reference standard for the V-200.

In 1968, the IDF advisors proposed to MID to build up an armoured brigade. The armoured brigade would have one AMX-13 battalion and two battalions of armoured personnel carriers for armoured infantry. The IDF advisers proposed that the M113 would be more suitable than the V-200 for the armoured infantry. They gave a number of reasons, which included better mobility, internal arrangement and less risk of delay in the build-up.

An M113 was brought to Singapore for comparison trial with the V-100 in 1968. The mobility of the M113 was found to be similar to that of the V-100 on dry ground, but was superior over wet ground.

The last demonstration on the swimming capability of the M113 was scheduled on 10th July 1968. During the final full-dress rehearsal just before the arrival of the Minister for MID the M113 sank in shallow waters. The demonstration was called off and MID made the decision to use the V-200 as the first SAF's APCs for the armoured brigade.



Wooden mock-up of the V-200 at Cadillac Gage, Warren, Michigan for fitting of On Vehicle Material (OVM) circa 1969

In January 1969, a team from the Logistics Division comprising Head Technical Department, CPT Lui Pao Chuen, mechanical engineer 2LT Lee Huan Shiang and Logistics Division ordnance advisor CPT Nehemia Zohar were sent to Cadillac Gage to decide on

the location of various "on-vehicle materials" (OVMs) for the V-200.

CPT Nehemia Zohar was a meticulous ordnance engineer and called for all the brackets for the OVMs to be mounted on bosses welded to the hull of the vehicle. The Cadillac Gage design team did not agree to welding bosses on the hull as the heat during welding would weaken the XAR-30 armour in the areas around the weld. They counter-proposed the use of tack welds to attach metal strips to the hull and for straps to be used to hold the OVM in place. The Cadillac Gage solution did not have a professional look. As it was unthinkable to compromise the integrity of the armour hull, CPT Lui accepted the Cadillac Gage solution proposed. CPT Zohar was very angry and did not speak with CPT Lui for three days. He eventually cooled down and accepted the decision.



CPT Nehemia Zohar, circa 1969

The prototype was shipped in October 1969, arriving dockside in Singapore on 20th November 1969 for test and evaluation.

MID refused to conduct prototype trials on this vehicle as it had not completed the 4,000 mile endurance test that was specified in the contract. Director Logistics ordered the vehicle to be issued for the training of officer instructors. A list of tasks and schedule of tests were prepared and passed on to 41 SAB for review and implementation as a part of the TEA programme for the V-200.

During a demonstration of its ability where the prototype was to climb up Bukit Timah, it broke down and had to be recovered.



First mobility trial of the V-200 prototype which broke down climbing Bukit Timah Hill, circa 1969

The prototype was loaded with the specified OVMs and simulated ammunition, and went for a swimming demonstration in Jurong River. The driver was the Cadillac Gage test driver who had been doing all the mobility tests in the US. However, the vehicle was never fully loaded in swimming tests before. The standard procedure of Cadillac Gage was to drive with the driver's hatch open. Soon after the vehicle entered Jurong River it was observed that the vehicle had a nose-down trim with less than 20cm of freeboard. Soon after, the vehicle was swamped by a wave. The driver floated out of the driver's compartment. The vehicle mechanic on the top of the hull swam off. The testing officer was knocked unconscious for two minutes by the wave. When he woke up he found himself in the hull completely filled with water. He found a door, opened it and swam to the surface.

A safety boat was present but the crew could not dive into the water that was about 20 feet deep. Since the sinking, the SAF Training Safety Regulation mandates the requirement for scuba divers to be on standby for testing and swimming training of land vehicles in the water.

The V-200 vehicle was lying on its side and could not be recovered by winching. A floating crane was hired from SELCO, a marine support company, to lift it from the bottom of the river and to bring it back to shore. The vehicle was brought back to the Vehicle Repair Base for cleaning up. The sinking ended all demonstrations with this prototype.

Production stopped as a result of the need to make design changes to the vehicle. The president of Cadillac Gage came to Singapore in February 1970 to seek MID's agreement to the changes made by the company in order that production could continue. MID agreed provided that the specified performance requirements in the contract were met by the production vehicles.

V-200 Mobility Trials

In the mobility acceptance test, the V-200 was found to be slightly superior to the V-100 for its cross-country capability and climbing of slopes as it had higher power-to-weight ratio and larger tires. However, both the V-200 and V-100 were bogged down in wet ground.



Mobility trial of the V-200 prototype up Bukit Batok Hill, with MAJ Lui Pao Chuen as the testing officer, circa 1969



The V-200 prototype undergoing mobility trials at Sungei Gedong, circa 1969

V-200 Weapon System Trials

It was found during a firing trial of the 20mm gun production vehicles that the accuracy of the gun was well within specifications, but stoppages happened because of the design of the ammunition feed system. The GK 204 20mm gun from Oerlikon of Switzerland was one of the best 20mm guns in the world. It was widely used by many navies as primary or secondary armament for their small ships. It was highly accurate with a high rate of fire that could destroy the weapon sight of a tank from the expected maximum engagement range of 800m.

In the operational analyses of the weapon systems, it was found that the confidence of the crew was critical to mission success. They must feel that they are well-protected from enemy threats and their weapon system would be ready for use during their mission. They must be able to find their targets and engage them before the targets disappear from sight. Thus the reaction time from target appearing to target destruction was one key parameter to optimise. Target detection and identification would be the responsibility of the vehicle commander and gunner. Weapon accuracy was important but the rate-of-fire was just as important to deal with fleeting targets. Action could be sustained as long as there was ammunition in the magazine but a weapon stoppage could be disastrous, especially when the enemy was returning fire.



Comparison mobility trials between the V-100 and V-200 at Sungei Gedong, circa 1970

The V-200 20mm gun vehicle could not play the role of tank killer but it was a fearsome predator to less well-armed and less well-protected weapon platforms. Enemy objectives defended by infantry would be suppressed by GPMG fire at close range and have their machine gun posts taken out by 20mm gun fire beyond the effective range of the machine guns.

The problem with ammunition feed was finally resolved and the SAF had the best 20mm turret in the world. This turret was subsequently sold by Cadillac Gage for upgrading of the V-100 and for the V-150 that the company built with the experience acquired from the V-200 project.

The V-200 90mm gun vehicle was less



Live firing trials with the V-200s with 20mm gun and 90mm gun at Sungei Gedong, circa 1970

successful. The V-200 was a light-weight armoured vehicle weighing 10 tons as compared to 40-ton MBT. The 90mm gun was made by MECAR of Belgium. The competitor was the DEFA 90mm gun made by a French company. The MECAR 90mm gun had softer recoil, making it more suited for the V-200.

The downside of low recoil forces was the low velocity of the ammunition. Despite the short range of 800m, the gun required super-elevation. Accurate estimate of range was necessary. There was no laser range finder then for range finding. The gunner would need to be trained to use the size of the target in his weapon sight to determine the range. Operation research was done to determine the reticle markings of the gun sight that would be best in assisting the gunner to determine the range in the shortest time, but not obscure targets further down range by the markings. Test officers spent many hours at the firing range to check on the accuracy of the gun and its reliability.



90mm gun on the V-200 with rope to limit angle of traverse for live firing at Sungei Gedong live firing range, circa 1970

The armour penetration required by the SAF was achieved with the use of hollow-charge ammunition. The penetrating power of the weapon was from the ammunition. During a confirmation firing trial of the 90mm gun vehicle at the Sungei Gedong range, the barrel of the MECAR 90mm gun disengaged from the recoil mechanism. The gunner was

the armour advisor, and the loader was the testing officer from the Logistics Division. The testing officer had the shock of his life when he saw the barrel flying in front of his nose and smashing into the VRC 47 radio set mounted at the end of the turret. His heart dropped when he saw a black beret between the gun barrel and the radio thinking that the head of the advisor was smashed. He was greatly relieved a second later to hear the voice of the advisor over the intercom. Before the firing exercise, the advisor had placed his beret at the rear of the turret when he put on the CVC (combat vehicle crewman's) helmet. The fault was traced to an error made by the gun fitter in assembling the gun for the firing. Testing of the 90mm gun was discontinued until arrival of the production gun.

The V-200 was found to be a stable platform for the 81mm mortar. The accuracy achieved was better than that when fired from the ground. Redeploying was very quick as the vehicle could be driven away immediately after firing.

The V-200 was, however, too light for the 120mm mortar which the artillery had wanted as mobile artillery in support of armour. The 120mm mortar prototype performed well at lower charges and its accuracy was good. But at the final test with the maximum charge of 8, the recoil force was too high for the vehicle.



The V-200 with 81mm mortar at live firing trial, Sungei Gedong live-firing range circa 1970

The V-200 engine was dislodged from its mountings, together with a number of other vehicular components.

The recoil force could be reduced to that of the 81mm mortar with a recoil mechanism. But the Artillery did not want any modifications to the 120mm mortar. The 120mm mortar vehicle could also be reinforced to resist the heavy loading of the firing at charge 8, but this would not have met the design concept of the V-200, of having commonality of components across the entire fleet. The General Staff Division thus decided to abandon the development project.

The need for artillery support with 120mm mortar was subsequently met when M113 was purchased for the second armoured brigade, and a battalion modified with a kit developed for the German Army for the 120mm mortar.

On completion of the test and evaluation programme for mobility (including swimming), weapon systems (firepower), armour protection and reliability, the project team handed over the V-200 to HQ Armour.

Litton was then supporting the missile gun boat (MGB) project with project management and engineering support, to deliver MGBs to the Singapore Maritime Command. Second Permanent Secretary of Defence (2PS) proposed that Litton be engaged to provide engineering and project management support for the V-200 production phase of the project. A Litton team led by Col (Ret) Gregg McKee relocated to Singapore and provided support for the programme.

Singapore Automotive Engineering formed to provide Maintenance Support for the V-200

There was a need to build up higher echelon maintenance. As Cadillac Gage had designed and built the V-200, the company would have the knowledge to develop the maintenance

support capability for the vehicle.

Instead of drawing technical manpower from the limited resources available to the SAF, it was decided in 1971 that SAE be established to support the maintenance of the V-200. Cadillac Gage was contracted to provide the initial technical leadership of the company.

This was the beginning of leveraging the expertise and technical manpower in our defence industries for depot-level maintenance of army vehicles.

V-200 versus M113

MID decided to acquire the French AMX-13 light tanks – the Singapore Army's first tank - in 1968. With the tip of the spear, the AMX-13s, inducted into the SAF Armour, the next crucial element was a vehicle for the armoured infantry.

Despite the V-200 being a technical success meeting all the stated requirements, it was an operational failure as the Armour found that it could not go through soft ground after rain and was left behind the AMX-13 during movement.

The Israeli advisors proposed that M113 would be more suitable a vehicle for the armoured infantry than the V-200. It would be able to follow the AMX-13 through terrain with wet ground. Besides the former's better mobility, there would also be less risk of delay in building up the brigade because the M113 was ready for production and had seen combat during the Vietnam War.

Instead of buying another 250 V-200s for the armoured brigade, Dr Goh Keng Swee accepted the recommendation of HQ Armour and the General Staff Division to buy the M113 which was in service with the US Army and many armies in the West. The concept of the M113 was a battle taxi, and it could also screen tanks from enemy anti-tank units.

Troops would dismount and charge up to capture the objective on foot.

While the M113 had better mobility, the new APC represented a step backwards for the SAF Armour in terms of protection, firepower, accuracy and weight of fire. The V-200s were better armed with a 20mm gun and co-axial GPMG in an enclosed, power-operated turret with optical sights.

The M113 came with a gunshield kit with a cupola and front shield to protect the vehicle commander manning a pintle-mounted 0.5" machine gun. Aiming of the 0.5" machine gun was by hand using iron sights. The 7.62mm GPMG mounts, fitted beside the rear troop compartment hatch, did not have shields. The front shield for the M113 cupola was eventually removed as the additional armour was deemed too heavy for SAF servicemen to traverse. The removal of the front shield degraded its armour protection, and resulted in a watered-down version of the US Army armoured cavalry's M113 configuration that recommended a gunshield kit for the 0.5" machine gun and additional armoured shields for the machine gunners firing from the troop compartment.

Although the poorer firepower of the M113 was later improved by the SAF with a 25mm gun in a turret, the gap would not be closed for nearly 30 years till the SAF introduced the Bionix.

Projects Spider and Archer

In the SAF of the 1970s and 1980s, the AMX-13 light tanks provided the mass, mobility and firepower. Already a credible war machine when first unveiled to the public as part of the 1969 National Day Parade Mobile Column, the Singapore Army's AMX-13s packed a punch right to the day these tanks were retired, with the last batch of full-time NSFs AMX-13 tankees trained around 2005.

Despite the inability of its 75mm gun then to destroy MBTs with thicker armour, the AMX-13 was no pushover in combat particularly in an operating environment with no tanks to fight against. Its 75mm gun represented a capability overmatch in the region.

Once training began in earnest on home ground, the pioneer batch of tankees grew to appreciate the performance of the AMX-13s in local terrain. With more tank battalions raised as a result of the steady intake of NSFs and the corresponding increase of NSmen battalions, MINDEF and the SAF planners realised that more AMX-13s would be needed to accommodate the growth of the SAF ORBAT during the 1970s.

The tank gun's versatility in firing different types of ammunition, accuracy and rate of fire (the AMX-13 was the first tank designed with an automatic loader and could fire one round every five seconds) was more than enough to deal with light armoured vehicles like armoured cars and enemy strongpoints like bunkers. The AMX-13's small size and ability to move cross-country quickly made the light tank ideal for supporting infantry assaults.

By the early 1980s, however, technology had caught up with the AMX-13 design. MINDEF and the SAF looked at alternatives to the long-serving AMX-13 because the tank was unable to serve the needs of the SAF Armour in its existing form. MINDEF sought a land platform with more superior firepower, mobility and survivability and intended to come to a decision point before the AMX-13s (still a formidable opponent in the early 1980s) became obsolete.

Due to the large number of AMX-13s that formed the spearhead of the Singapore Armoured Regiments, time was of the essence. If the procurement process was delayed to the point that the AMX-13 was outclassed by contemporary armour, then MINDEF

risked allowing the SAF's tank force to reach block obsolescence before a replacement was found or before a new vehicle time reached full operational capability. This could have had serious implications for the operational readiness of the Army's manoeuvre units and the deterrent effect of the SAF.

In 1984, a team was formed between MINDEF and SAE to assess the viability of either upgrading the AMX-13 tanks or replacing them altogether. The project was codenamed Project Archer. At the time, a light tank replacement was said to cost around S\$3 million. This compared to the projected cost of upgrading the tank, which was estimated to be around one-fifth that amount.

The gun that armed the AMX-13 had an impressive history that impressed the Israelis in the 1950s. This was before the Israelis discovered that the AMX-13 gun could not penetrate Soviet-made T-54 and T-55 tanks used by Arab armies such as the Egyptians and Syrians.

The book *Chariots of the Desert* described why the gun impressed the Israeli army, "At the time the French had developed a fast-firing 75mm tank gun, which was a development of the powerful German 7.5cm KwK 42 (L/70). While this gun reached a muzzle velocity of over 900 m/sec for anti-tank ammunition, the French CN 75-50 gun topped 1,000 m/sec and, in those days, was considered the best tank gun in the world. Mounted on the oscillating turret of the air portable light AMX-13 tank, it fascinated the Israeli tankers; their own guns still being obsolete short barrelled 75mm M3s reaching a mere 600 m/sec."

Project Spider, which was declassified for this book years after the AMX-13s were retired by the SAF, was the codename for the project that sought to develop an improved anti-tank round. The project was started to leverage the 75mm gun's high muzzle velocity to propel an armour-piercing dart right through thicker armour plate.

Led by engineers from CIS in the early 1980s, Project Spider led to the development of the world's most powerful 75mm tank round – a dart-shaped tank-killer that gave the 18-tonne AMX-13 SM1 tank the ability to destroy larger and better protected tanks many times its size. The new munition was known by its full name as the Armour-Piercing Fin-Stabilised Discarding Sabot Tracer (APFSDS-T) round. Among those in the know, it was simply called Spider. The Spider round was innovative as it was one of the few sabot rounds in the world that was fired from a tank gun with a muzzle brake.



AMX-13 SM1 tankees with the Spider 75mm APFSDS-T rounds

The success of Project Spider paved the way for MINDEF to approve Project Archer, the full modernisation of the AMX-13 light tanks to SM1 standard. MINDEF would not have considered upgrading the AMX-13s if the firepower of the tanks could not have been improved. The success of Project Spider was therefore the start point for the fresh lease of life for SAF Armour's ageing warhorses. Thanks to the new, more lethal munition, the 75mm main gun on AMX-13s could engage and destroy bigger and better protected armoured vehicles like MBTs. Generations of SAF Armour tankees entrusted with this knowledge had kept their oath of secrecy and this capability had remained secret past the tank's retirement as it represented an advantage that could catch a potential opponent tanks off guard in combat with no defence against the armour-piercing rounds.

The AMX-13 Light Tank Design

From a technical standpoint, the AMX-13 design had two noteworthy achievements to its name:

- The AMX-13 was the first tank designed with an automatic loader. This gave it the advantage of a high rate of fire, with one aimed round every five seconds.
- It was the first tank designed with an oscillating turret.

A 1967 booklet, titled *AMX-13 Armour In Profile*, described the light tank's design features. "The advantages of the oscillating turret concept are principally that it simplifies the design of an automatic loader because it allows this device to be mounted in the turret, which moves with the gun. This means the gun breech, irrespective of its position, is always in the same relative position to the automatic loader, mounted behind the breech at the rear of the turret. If the gun in a normal turret is depressed, so the breech gets closer to the turret roof and, unless the roof is made abnormally high, there is an obvious limit to this movement which is even further restricted by the space required for loading. Alternatively, the gun can be mounted low in the turret to achieve greater amplitude without having a high roof but, if this is done, the depression of the gun is limited by fouling the hull front. With the oscillating turret, the gun can be mounted high in the turret, which means that the minimum area of turret is exposed to the enemy when engaging a target from a hull-down position. This also means that because the gun is mounted high in the turret the hull front should not be a limitation to the amount of depression of the gun. In a tank this is of vital importance tactically."

There was a flip side to this 1950s-era design, which armies fielded as a tank destroyer and mobile gun. *Armour In Profile* described the shortcomings of the design: "The oscillating turret does suffer some basic disadvantages inherent in the design which undoubtedly explain why the concept has not been more widely adopted. More power is required for elevating and depressing the gun than in a conventional tank. Total armour weight is greater because of duplication of armour thickness where the two parts of the turret overlap. The clearance between the top and bottom parts causes problems in sealing the turret in a chemical or nuclear environment and in wading operations. There is also the hazard of the turret becoming jammed by foreign matter, or even small arms fire on the battlefield."

Project Archer was a watershed for Singapore's defence industry. It marked the largest and most complex AFV modernisation planned and executed by Singapore's defence science and engineering community. It involved a near 100% rebuild of SAF AMX-13s at SAE's Portsdown Road workshop. In short, each AMX-13 was taken apart and completely rebuilt using state-of-the-art components. As traffic on the Ayer Rajah Expressway zipped past the workshop – tiny by American and European standards – SAE's engineering staff gave a new lease of life to the 1950s-era tanks by replacing ageing components like its engine, transmission, suspension, radio and weapon sights with new components specially-picked to improve the AFV's combat capabilities.

The MINDEF-SAE team modified two AMX-13s in 1985 as test beds for the proposed upgrades. By 1986, the Archer prototypes were ready for field trials. Initial trials took place from April to October 1986. Test results were analysed closely, modifications proposed and refined and by the end of 1986, the design freeze for an upgrade package was finalised. Upgraded vehicles were known as the AMX-13 SM1. This somewhat lengthy name was eventually shortened to simply SM1.

On 15th June 1988, the AMX-13 SM1 Commissioning Ceremony was held at SAE's Portsdown Road plant. Speaking at the ceremony, MG Winston Choo, then Chief of the General Staff of the SAF, said, *"The AMX-13 upgrade project has shown that with imagination and innovativeness, much can be achieved with existing means. This possibility of adaptation and upgrading must be constantly borne in mind, as the maturing SAF grapples with the fast changing technology."*

MG Choo said two reasons underlined the decision to upgrade rather than buy new tanks. First, there existed "excellent possibilities to upgrade the tank to meet our operational requirements" at a fraction of the price of buying a new vehicle. Second, the fact that

the project involved home-grown defence engineering know-how would give Singapore's defence technology capabilities a significant boost. With the upgrade in full swing, MG Choo noted that "our defence industries have grown in experience, capabilities, reliability and are well-trained to help the SAF."



Official Commissioning of the AMX-13 SM1 Tank by then CDF, MG Winston Choo on 15th June 1988

After four years of effort which resulted in the AMX-13 SM1, MG Choo said the "the outcome is a tank that is affordable and meets the operational requirements."

When the AMX-13s were retired, Singapore operated the most powerful AMX-13s in the world. The Singapore Army's AMX-13 tank force was also the world's largest. Credit for their operational readiness and hitherto unknown combat capabilities goes to the efforts of Singapore's defence scientists and engineers, who exercised ingenuity in keeping the 1950s-era French-made tanks lethal some 50 years after they were manufactured.

The AMX-13 modernisation provided the Singapore's defence engineers a valuable opportunity to learn first-hand the technology, characteristics and trade-offs in protection, mobility and firepower. It also served as a springboard for more complex and ambitious projects by Singapore's defence scientists and engineers, with the development of the first AFV designed and built in Singapore the inevitable outcome. But success did not come automatically or easily.

AMX-13 SM1

By Loh Heng Fong

Mechanical Engineer Mr Loh Heng Fong gives a first person account on the AMX-13 upgrading programme.

The AMX-13 was acquired by the SAF in the 1960s. At the time, it had manual transmission that gave tank operators something extra to worry about and a rudimentary suspension design that did not give the soldiers a very comfortable ride. Our team had been given an opportunity to modernise the AMX-13 fleet for the SAF. The SM1 programme was to make the tank faster, safer and more economical to maintain. In giving the AMX-13 a new lease of life, we had fitted the vehicle with a diesel engine, fully automatic transmission to improve vehicle handling and a hydro-pneumatic suspension system to provide soldiers with a smoother ride. The refurbished AMX-13 SM1 tanks were the first in its class of light tanks to have hydro-pneumatic suspension. Lifting a quote from the HQ Armour Heritage Centre, "The AMX-13 project was a test of Stamina, Teamwork and Cooperation between HQ Armour, DMO and ST Kinetics. We overcame seemingly insurmountable problems on the journey together through uncharted terrain, and it was a huge success".

Humble Beginnings

I was working in an oil refinery industry as a project engineer and was introduced by my university classmate to join SAE in March 1982. I was designated as an Engineering Executive (EE) in the Engineering Department. There were only 30-odd staff with about 10 draftsmen and draftswomen and 20 odd engineers; most of them were Engineering Assistants (EAs).

I was an Artillery NCO when I served my NS. I did not have any knowledge in military vehicles. I should have joined ODE instead of SAE; however I preferred automotives to

weapon systems.

As a Junior EE, I was assigned a number of projects and AMX-13 dieselisation was one of them. My responsibility was to assist the existing dieselisation team, which consisted of a Senior EE who was the project engineer and four EAs reporting to the engineering manager. The main scope was to look for a suitable diesel engine in the market and to replace the obsolete petrol engine by a higher-power diesel engine.

The Challenge

The challenge for the design team was to install a complete higher-power diesel engine pack including radiator, fan and fan drive, air cleaner, air induction system, exhaust system and cross-flow radiator into the confined engine compartment of the original AMX-13. In other words, the new requirement was to increase the engine power by 20% without increasing the size of the engine compartment. With all these challenges, the most difficult task for the design team then was to design a suitable integrated cooling system for the new diesel engine and the existing control differentials which provided the steering function for the AMX-13.

After talking to the project team, I was told that a number of cooling system designs had been attempted but none of them seemed to work. The radiator was under-sized, causing over-heating of the engine, and there was oil leakage from hydraulic fittings of the cooling fan system due to vehicle vibration.

As an inexperienced engineer, I did not undergo any formal training - everything was self-driven. I learnt through reading magazines, military articles and product brochures. To learn more about the mechanical designs of every system and pick up some hands-on experience, I worked most of the time in the company workshop or army camp workshop when vehicles broke down. To



SAE's working team in front of the AMX-13 SM1 at its Portsdown's test track.
Mr Loh Heng Fong is in the front row second from the left

learn the function of the vehicles and get field experience, I followed my senior to the testing ground in Sungei Gedong Camp. During vehicle trials, I took the opportunity to learn to drive as well as learn about the maintenance of the vehicle. Besides learning from my senior at the time, there were very experienced mechanics in the workshop I learnt from. They would sometimes scold you when they saw you doing something silly. However, in order to make them feel good so as to continue to learn from them, I tolerated!

Unexpectedly, after been working in the company for about a year, my senior suddenly resigned. I was appointed the project engineer with the responsibility of leading the four experienced EAs. At the time there were still many technical problems that needed resolving, such as engine over-heating, oil leakage due to vehicle vibration and some reliability issues. I was telling myself, if the project team had been working hard for more than two years and yet still could not find a workable solution, then there had to be something that they didn't do right!

I knew the first thing I needed to do was to look for another engine which met all the requirements set by the SAF, but what was

this engine? It so happened that Detroit Diesel Allison had developed a new generation of turbocharged engines known as the Silver 53. This was a very compact engine which improved engine performance, fuel economy, reliability and durability. I contacted the local agent, General Diesel Singapore (GDS). I worked very closely with its sales manager, its service manager and even its workshop technicians. They provided me with a lot of technical data about the Silver Engine. From this data, I was able to learn more about the two-stroke diesel engine. I finally selected the 6V-53T engine. With all the knowledge I learnt from GDS I was confident in calculating design requirements for the associated auxiliary systems such as cooling systems, air filtration systems, exhaust systems and fuel systems.

However, this was just a paper study and needed to be translated into hardware. My next challenge was to size out the radiator for the engine, coolers for the transmission and steering differentials, cooling fan for the radiator and coolers, and air filters and exhaust mufflers. After many meetings and discussions with the sales manager at GDS, he advised me to look for overseas suppliers. I was recommended to contact suppliers

such as Airscrew Howden for cooling fans and Galley for radiators from the UK and Donaldson Company Inc. from the US for air filters and mufflers. This was the time during which I had opportunities to travel overseas and talk to experts and overseas designers directly. I took the opportunity to visit their workshops and to understand their design and manufacturing processes. It was really an eye-opener for me. While so, it was not sufficient just to have all this knowledge to size the engine's associated systems. As mentioned earlier, the main challenge was to assemble all these systems and house them into the very small and confined AMX-13 engine compartment.

My worry came true after all the systems were sized up. The entire engine pack required a bigger engine compartment in order for all the systems to work accordingly as the design intended. During that time, we did not have good knowledge to modify the original AMX-13 chassis which concerned armoured steel material. To gain more space, unavoidable hull modification was necessary. Our question was, could we cut and modify the original AMX-13 hull built in the 1950s?

Turning Point

At last, the SAF put up its request for two prototypes to select a suitable one. The requirement was to change the petrol engine and manual transmission to diesel engine with automatic transmission. It was very obvious that they needed an automatic transmission as the original manual transmission was not easy to operate by the SAF's newly recruited drivers. On some occasions the driver's hand may get injured because of the kick-back action of the gears during gear shifting. To fulfil the SAF's requirement to have two dieselisation kits for them to evaluate and chose one, we first had to look for a suitable automatic transmission for our existing diesel engine kit and second, develop another completely different power pack (comprising complete engine and

transmission systems) for the SAF to choose the best. The SAE management understood the technical challenges of the SAF's new requirement and the limited knowledge our team had. In order not to overload our team, an overseas partner was brought in as they claimed they had a proven dieselisation kit for the AMX-13. Its kit consisted of a two-stroke 6V-53T Detroit Diesel engine of a different model from ours and its in-house developed semi-automatic transmission. The company had had many experiences with tank retrofitting projects, which ranged from the US M-series medium tanks through the Soviet T-series and the British Centurion.

For our existing kit, I had to look for a suitable automatic transmission to match with the Detroit Diesel 6V-53T engine. After some market research and literature search, we finally selected ZF. ZF was a German company producing thousands of transmissions per day, which they supplied to car and truck companies. They also designed transmission for military applications. I started working very closely with ZF's local office as well as their HQ design office in Friedrichshafen, Germany. Eventually their chief design engineer, an experienced old man of 70 over, recommended modifying one of their well-proven commercial transmissions ZF WG-180. Mr Toh Beng Khoo was the engineer in DMO (Defence Materials Organisation, now DSTA) who travelled with me to ZF Germany and we worked with the Chief Design Engineer in his office for almost one month. The objective was to learn more about the ZF WG-180 transmission and to discuss the necessary modification required in order to reconfigure this transmission to fit into the existing AMX-13. Both of us learnt a lot about automatic transmission in terms of the matching of transmission with engine, torque convertors matching and selection and gear shift patterns. We also visited ZF's transmission and steering system manufacturing plant in Friedrichshafen as well as Passau office.

As for the other kit, a separate team was set up to work with the overseas partner. They worked in another workshop led by a very experienced chief engineer. The project engineer from SAE was Mr Mah Chi Jui. The chief engineer knew that SAE was also developing a diesalisation kit. Instructions from the management given to us were not to copy their designs and also not to go near their work area. As a young and curious engineer then, I just wanted to know how they actually did it? I had no intention to copy any of their designs.

Occasionally I met Chi Jui and tried to understand a bit more about the kit he was working on. I did not get too much detail but tried to understand in general how the hull modification work was being carried out and the layout of the engine and its associated systems. While having more dialogues with Chi Jui, I was inspired by two very important pieces of information. The first was that the chassis could be flame cut and modified to increase space in the engine compartment. Secondly, the kit used mechanical means to propel the cooling fan instead of hydraulic means. In other words, our problems of space and hydraulic oil leakage due to vibration could be readily resolved.

The Solution

With this information, we started working day and night to reconfigure a new layout. The first thing to do was to modify the existing engine compartment by cutting out a portion of the side hull and to create more space for the cooling fan. Concurrently we communicated with ZF, Airscrew Howden, Galley and Donaldson to change some of their proposed designs to accommodate the space we allocated for their systems. To change the hydraulic fan drive system to a mechanical system, we contacted a gearbox manufacturer to design and fabricate a mechanical gearbox for the cooling fan. For the new engine and transmission, we required some of the information to be displayed in the Driver Instrument Panel (DIP). Therefore I

contacted the local VDO office and they linked me up with their design office in Germany. A new DIP was then designed for the SM1.

With all these studies, the next challenge was to do a complete mechanical system integration to link up the entire engine and transmission associated systems, which required calculations, design and preparation of engineering drawings. We had to discuss with local and overseas vendors for the fabrication of all the sub-system parts such as brackets, electrical harnesses and mechanical control linkages. In the early 1980s, we did not have finite element method (FEM), computer-aided design and manufacturing (CAD/CAM) or any simulation design tools to help us, everything was done in a conventional way – hand calculation, hand sketch and then drawing board. One thing I would like to admit was that the overseas' kit provided me with some confidence. For instance, I was not too sure sometimes if the size of a bracket was done correctly as I did not know the correct design safety factors to adopt. Referring to the similar bracket used on the kit, I could counter-check and it became our reference guide in the future.

Similarly during those days, we did not have proper design guides and design processes such as Standard Operating Procedure (SOP) and Work Instruction (WI) to guide us along. In other words, we had a very lean process and therefore things moved very fast. I was allowed to do anything I thought was correct and to make a final decision on my own as there was no better and experienced engineer or manager there to give me advice. For me, this provided me with a good opportunity to exercise my ability to deal with engineering problems as well as my management skills. At times, I need to work in local vendors' fabrication workshops with their workers and technicians. There was a small SAE machine shop at Portsdown and I often worked with the machinist for minor modification works. I understood that if you wanted to learn more

from people, you had to be humble and in return you would get all that you want as well as respect.

The Hardship and the Fun

Although I mentioned earlier that there was no experienced engineer to guide me along, I did have two very experienced EAs, Mr Anthony Leong and Mr Sunny Kang. Anthony was an experienced mechanical EA and an experienced test driver. Sunny was experienced in electrical and electronics. Both had no diploma qualifications but all their experiences were learnt from years of hand-on and field trials in Sungei Gedong Camp or overseas testing grounds. We did not have a big testing team during those days and therefore everyone in the team had to take turns to be the driver and vehicle commander. For safety reasons, the SAF did not allow us to drive the AMX-13 without the SAF driving licence. Therefore we had to be trained by the SAF driving instructors and finally took a test in order to obtain a driving license issued by the SAF. Testing a vehicle in Sungei Gedong was also not a fun thing to do! There was no training shade in the field for you to rest while you were waiting for your turn to be the driver or commander. In order not to be exposed to the hot sun, we either rested under trees or hid inside the company truck when it was raining. There was a coffee shop outside the camp and very often we took our breakfast and packed our lunch and dinner



Sungei Gedong Test Ground Condition

there. When the test vehicle broke down, we had to arrange transport to either tow the vehicle back to the camp workshop or back to Portsdown workshop. Occasionally there were ad hoc vehicle demonstration trials to VIPs from the SAF, and we had to work overnight either in Sungei Gedong workshop or Portsdown workshop to make sure the vehicle was in tip-top condition for the trial.



AMX-13 SM1 Towing Test

The Final SM1 Kit

Finally SAF had to decide which diesalisation kit they would choose for production. The two options were: Overseas' kit with semi-automatic transmission where the driver was still required to upshift or downshift the gear selector while driving, or SAE's kit with fully automatic transmission where the driver only needed to select a driving mode before the vehicle moved out. The SAF eventually selected the SAE kit but they wanted us to look into improving the suspension systems as well.

The original AMX-13 was designed with torsion bars system for its suspension. The disadvantage of the torsion bar suspension was a lack of progressive spring rate and therefore it offered less stability when travelling in rough terrains. With the new diesel engine and fully automatic transmission, SAF expected the vehicle to travel faster in cross-country terrains while providing good stability for the gunner and commander as they were

operating the turret. Two suspension systems were evaluated. The first was GLS from Germany which had proposed dual-action hydraulic telescopic shock absorbers with hydraulic bump stops, and the other one was Dunlop's hydro-pneumatic suspension system. Two systems were evaluated and finally due to some reliability issues on GLS's system, the winner was the Dunlop's hydro-pneumatic suspension. The AMX-13 SM1 thus became the first in its class of light tanks to have hydro-pneumatic suspension.

With all the improvements mentioned above, the crew liked the SM1 very much not only because of the improved suspension system, the automatic transmission and higher power of the diesel engine, but also the way the cooling system was being arranged in the vehicle. Most vehicles installed air conditioning or an air blower system to improve crew comfort. However, for the SM1, we made use of the engine cooling fan to provide cooling not only for the engine and transmission but also to provide air circulation for the driver, gunner and commander, thus reducing the number of components used on the vehicle. This led to reduced production cost, lower maintenance requirement and lower overall life-circle cost.

XV1 – Forerunner of Singapore's first indigenous Infantry Fighting Vehicle

When defence engineers in Singapore assembled an experimental armoured vehicle in early 1990s to demonstrate their readiness to design and build an AFV, the home-made vehicle almost fell apart when taken for a test drive.

As the experimental vehicle, named XV1 (eXperimental Vehicle 1), was coaxed to move faster over rough terrain at the SAFTI live-firing area, a road wheel came off in a somewhat inelegant display of engineering failure. The XV1 chassis moved ahead while the loose road wheel rolled off sideways on its own journey.

Engineers from SAE could have called it quits there and then. With so many AFV types to choose from, Singapore could have bought a foreign AFV off-the-shelf.

To their credit, the SAE team did not give up. XV1 was repaired and joined by a stable mate, XV2, and the rigorous trials on these experimental vehicles eventually paved the way for the development of the Infantry Fighting Vehicle (IFV) designed and built in Singapore. This IFV was named the Bionix.

The evolution of the Bionix took place within a few years. From 1988 to 1990, the SAF and defence industry explored the possibility of fielding a successor to the M113. After the paper studies, an Experimental Vehicle Programme started in 1990 led to a test bed design review in March 1992 which gave rise to the early Bionix prototype – a fully tracked armoured vehicle with a front-mounted engine and rear troop compartment that represented a rudimentary IFV concept.

This was followed by the roll-out of three test beds for field trials in quick succession: XV1 in January 1993, and XV2 and XV3 in the middle of 1993.

The following year proved a busy one for the project team, codenamed Funby as it was a “fun” vehicle project. The final test bed design review took place over four months from April to June 1994, with three final prototypes rolled out from 1995 to 1996.

Extensive testing in Singapore and overseas, which included mobility trials across thousands of kilometres, led to the pre-production model roll-out in June 1996. By September that year, the IFV that one would recognise as the Bionix was ready and the final design review was signed off in 1996. This led to the initial production of the IFV on the new assembly line and the roll-out of the first production IFV in August 1997.



XV1 Prototype



XV2 Prototype

Despite the initial failure, what was the source of confidence that motivated SAE engineers to push on?



Bionix Infantry Fighting Vehicle in action

It was their experience driving the modernisation project for the Singapore Army's AMX-13 tanks. Accomplished in 1988, which was the same year the SA introduced the 155mm FH88 field howitzer – the first heavy artillery gun designed and built in the Lion City - Singapore's defence planners were in a buoyant mode. The question on everyone's mind was what's next? Why not an indigenous AFV?

The can-do spirit of Singapore's defence scientists and engineers has contributed immeasurably to the defence of the Lion City. This was achieved by expanding the range of engineering capabilities to improve armoured war machines used by the Army and the RSAF, which uses V-200 armoured cars armed with RBS-70 low-level air defence missiles. More importantly, every defence professional who contributed to AFV projects helped to nurture a new generation of Singaporean defence scientists and engineers with the know-how, track record and managerial expertise at delivering unique AFVs designed for the Singapore Army's specific operational requirements.

For a small country with no national car and hence no legacy of deep expertise in automotive technology, Singapore's ability to design, build, manufacture and maintain a growing list of indigenous armoured vehicles has raised eyebrows amongst military analysts and defence companies worldwide.

The attention of defence analysts is heightened further when they better understand what Singapore-made AFVs can do. This includes the best-in-class cargo and cross-country performance of vehicles like the Bronco all-terrain tracked carrier. The design features of the Bionix have also attracted attention. The Bionix's design strikes a balance between protection, mobility in confined spaces like rubber and oil palm plantations, and the amount of integration aboard and between the AFV and other SAF assets that allow information to be harnessed to gain the best advantage during operations.



The Bronco all-terrain track carrier deployed in action

Years after the Bionix was unveiled in 1997, defence engineers and management from its maker, by then known as ST Kinetics, continued to field queries – some asked discretely, some less so – about which foreign company helped Singapore design the Bionix. A follow-up query when ST Kinetics replied that the design was done locally: Which AFV “inspired” the Bionix design? The less subtle asked point blank which armoured vehicle design was copied to make the Bionix.

The capability jump in AFV technology evidently caught many foreign defence watchers by surprise. The reply from ST Kinetics that the Bionix was developed in Singapore by Singaporeans was initially greeted with incredulity and scepticism.

As more AFVs designed and built by Singaporean know-how, such as the Bronco, the Primus 155mm self-propelled howitzer and the Terrex 8-wheeled infantry carrier vehicle, rolled off the ST Kinetics assembly line, such scepticism were eventually silenced.

The creativity of Singapore's AFV project teams is seen in innovations such as the use of rubber tracks on the Bronco (this makes the vehicle quieter and gives a more comfortable ride compared to steel tracks), the development of the world's most powerful 75mm tank gun ammunition and the adaptation of the basic Bronco design into some 30 specialised variants from troop transports, mortar carriers to missile-armed anti-tank platforms.

Tough Customers

Anyone who is looking at the growing list of armoured vehicles produced by ST Kinetics over the past decades might assume that Singapore's defence industry has enjoyed a smooth, problem-free growth trajectory as it delivered increasingly complex projects. Singapore's AFV development journey was anything but an easy ride.

Singapore's defence scientists and engineers knew better than any of their counterparts that MINDEF and the SAF are tough customers who needed to be convinced that Singapore's defence industry is capable of far more than just maintenance and final assembly of war machines supervised by a foreign vendor.

They have to fight hard to win the trust and confidence of MINDEF and the SAF. Their successes at overcoming technological and design challenges have seen Singapore gradually expand its indigenous AFV family to include tracked and wheeled armour, as well as specialised armoured vehicles such as bridge-layers to span gaps like canals and mine-clearing vehicles for demining operations under fire.

The project to upgrade the whole fleet of AMX-13s for the Singapore Army nearly went by default to a foreign company as MINDEF and the SAF had yet to be convinced the work could be done in Singapore. By stepping forward with their proposal for modernising the 1950s-era tank at a price and with capabilities no other company could offer, our defence scientists and SAE engineers forged trust and confidence with MINDEF and the SAF Armour.

The XV1 capability demonstration may have had a modest start. But perseverance paid off as the Bionix that emerged is the world's best-protected IFV that can manoeuvre in plantations and confined areas in an urban battlefield.

Despite the competition from more established rivals, it was the ability of our defence scientists and engineers not to lose heart too quickly and to bounce back quickly after engineering setbacks that set Singapore's AFV journey on the proverbial road to success.

Over time, Singapore's defence engineering community learned to build on modest quick wins and, more critically, adapt and learn from engineering blind alleys. The latter includes failed attempts to install a 155mm gun onto a truck and the effort to modify the AMX-13 tank for swimming.

Singapore's AFV development journey packs an inspiring storyline. But it is worth understanding why Singapore goes the extra mile to customise AFVs. Why not simply buy off-the-shelf?

Why Made in Singapore Matters

If you can drive a car safely, it is likely an SAF instructor can teach you how to drive off in a Singapore-made armoured vehicle in 15 minutes or less.

Starting up a Singapore-made AFV takes just two easy steps. Activate the main electrical switch, then press a button to start the engine.

Whether wheeled or tracked, Singapore-made AFVs are designed to be easy to drive right from the design stage. Instead of wrestling with steering levers (one for each track) on a typical tracked vehicle, the driver moves the Bionix and Bronco using a small steering wheel the same way civilians steer a car. The floorboard has only two pedals: an accelerator to move forward and a brake to stop. This compares with older designs such as the AMX-13 and M113 which had a clutch, an accelerator and a brake pedal. With no clutch, an automatic transmission takes care of the job of shifting gears. This means driving is made easier and less taxing. The benefit of having a vehicle that is simple to drive is seen during sustained operations at long range. The driver's alertness is improved, which translates to a safety ride for those aboard the vehicle.

For a city-state that relies on NSmen and NSF's as the main sources of defence manpower, it is critical that the time spent training and refreshing their combat skills is used productively.

Designing AFVs to be simple to operate and maintain accelerates the learning for NSmen and the younger NSF's, and makes the vehicle more soldier-proof. But this is just one aspect of a wider, more holistic effort at revamping the training syllabus for AFV crews. This revamp has led the SAF Armour to introduce driving and gunnery simulators to train Bionix and Bronco crews. These simulators realistically immerse AFV crews in terrain and expose the soldiers to threats and operational situations they may face in combat.

Time spent training with the AFV can therefore concentrate on the forging teamwork between the AFV crew and embarked armoured infantry. Higher order skills such

as the coordination needed between armoured vehicle commanders and their crew to fight as a team as part of a platoon, which is part of a company in a Singapore armoured regiment are also regularly practised during war games.

During annual call ups, NSmen can quickly familiarise themselves with war machines they were trained to use during their two years of full-time NS. Once reacquainted, the NSmen can concentrate on refreshing battle skills in their armoured battalion and practise large-scale manoeuvres as part of an Armoured Battle Group (ABG).

A war machine that is easy to operate and maintain is invaluable for Singapore's citizen armed forces and keeps maintenance costs low from the time the vehicle is put into service till it is retired years later.

Singapore-made AFVs place heavy emphasis on protecting the crew because the life of every Singaporean who serves the SAF in peace and war is important. A high level of crew protection can be accomplished with careful trade-offs in the three principal design considerations of protection, mobility and firepower faced by all AFV designers.

Addressing one design consideration often came at the expense of the others. This means all AFV designs must strike a balance between the war machine's ability to destroy targets (firepower), move on the battlefield or in water (mobility) and safeguard its occupants and vital systems from enemy fire (protection).

First, the level of protection for an AFV depends on its armour. In today's context, stronger armour does not necessarily mean heavier armour. This is because composite armour has evolved to give AFV designers options that do not come with a stiff weight penalty. For example, the Bionix, Bronco and Terrex all leverage advancements in composites to protect their occupants with a higher level of protection while keeping the vehicle's weight

low. The last point is important as a vehicle's cross-country performance is determined to a large extent by its weight and engine performance.

Second, emphasis on mobility could result in making the AFV more survivable as a fast mover is harder to target and hit. An AFV that is highly mobile can also mean it can travel on rough ground or soft terrain which is impassable to less-mobile designs.

Third, the AFV crew could be armed with the firepower needed to address threats that could be used against the vehicle. Should you pick a gun, a missile or a mix of both? If a gun is selected as the main armament, what size of gun? A bigger calibre or size of the shell means the vehicle can carry less ammunition. A larger gun also tends to have a lower rate of fire, which means fewer shells on target compared to a lighter weapon that can put more rounds on target faster. The SAF learned from experience with the V-200 armoured car that a bigger gun does not necessarily mean more firepower. The 90mm low pressure gun in the V-200 has a poorer armour penetration compared to the 75mm gun on AMX-13 light tanks.

In addition to careful considerations of trade-offs in protection-mobility-firepower, Singaporean AFV design teams identified an additional factor: information.

By design, the crews of an AFV fighting with hatches closed rely on their armoured periscopes or radio communications with other vehicles to make sense of the unfolding battle situation around their vehicle. The number of periscopes on all armoured vehicles is deliberately kept low as the breaks in the cast or welded armour needed to fit the vision port can compromise the level protection. The periscopes provided for a tank driver can usually be counted on one hand. A tank gunner seldom has a 360-degree view of the outside world.

The tank commander would typically be furnished with a better view of the outside world with more periscopes on the cupola. However, battle experience has led many armies to train their tank commanders to fight from an open hatch as the awareness of the situation is deemed more critical to the AFV's survivability than simply going into battle with all hatches closed. Pictures of SAF tanks during war games that commonly show the tank commander fighting from an open hatch indicate how SAF Armour trains its tank crews to go into battle.

It is counter-intuitive because one would suppose that the tank crew is better protected when all hatches are closed, as opposed to the situation when the commander has his head and shoulders exposed to enemy fire.

Technological advancements have allowed Singaporean design teams to strike a compromise. For example, by designing AFVs with a locally designed Battlefield Management System (BMS) that furnishes the commander and crews with information on threats around the vehicle. The BMS is designed to enhance survivability by giving them forewarning of areas to avoid, even when the AFV operates with hatches closed.

Aware of the decisive edge that information could deliver to warfighters networked to fight as a system rather than as individual platforms on the battlefield, MINDEF, the SAF and ST Kinetics made a conscious decision to exploit advancements in communications and information technology to wield information as a weapon. A gun or missile is only lethal when the crew knows where to aim. This push to allow AFV crews to see first, see more, understand better and act decisively explains why new vehicles from Singapore's battle labs are wired up to a greater extent with datalinks, flat screen displays and even tiny electronic cameras that served as "eyes" around the war machine compared to armoured vehicles the SAF had bought from overseas. Information is a force multiplier.

One feature unique to AFVs designed and built in Singapore is a high level of armour protection packed into a relatively narrow vehicle body – typically less than three metres wide. By deliberately designing to a certain size template, AFV commanders can move their compact yet well-protected war machines in restrictive terrain such as urban areas and plantations, which larger vehicles could not bypass. Off-the-shelf AFV designs designed for European battlefields or combat in open deserts are unsuited for the SAF's operating environment because terrain such as plantations will prove impassable to larger and wider fighting vehicles.

The decisions that lead the SAF to introduce, renew or retire its armoured vehicles are classified to protect the operational or technological advantage that such war machines offer the SAF. The process can, however, be described in general terms because they follow principles for project management commonly practised for large-scale projects. These include:

Statement of Needs: This document drills down what the SAF needs in that capability in terms of design and performance.

Specific Operational Requirements: Complementing the Statement of Needs is the listing of operational requirements that further shape the capability required.

Concept of Operations (CONOPS): This states how the capability will be employed, for example, an ability to engage and destroy enemy AFVs at long range, why it is required and what kind of existing and projected threats it may have to address. The CONOPS will spell out whether the capability should be represented by attack helicopters (like the AH-64D Apache) or in a new AFV.

Operational Master Plan: The SAF spells out how the capability will be introduced, and timelines required.

Engineering Master Plan: Technical aspects of the capability, which will guide how the capability is maintained throughout its service with the SAF, are stated under this plan.

As CONOPS is articulated, debated and refined by the weapons staff and the technical side of the house represented by DSTA, the defence industry and the defence science community such as DSO, the project team relies on the SAF's experience operating various weapon platforms and DSTA's expertise in testing many others to get a better feel of what is required.

By this stage, the capability would have been defined more specifically. For example, the weapons staff would have decided that the anti-armour capability will come in the form of an AFV instead of an attack helicopter with anti-tank missiles or a special anti-armour artillery munition.

Along the way, the planning cycle will leverage on Operations Research, which refers to the analysis of accumulated defence data and field experience, to outline the capability that might suit the SAF. Computer modelling and simulation allows paperless design and speeds up the process for the project team to get a better sense of the weapon being developed.

The validation and refinement of the various plans is also critical. The SAF uses computer-aided war gaming and field trials involving two-sided (Blue team versus Red team) and multi-sided encounters involving the Army and RSAF units, to ensure these concepts go through trial-by-fire.

Demonstration units such as 42 SAR that are equipped with an initial batch of the new AFV provide valuable end-user feedback on the comfort, ease of use and maintenance requirements. Such feedback ensures the technical manuals that guide how the AFV is operated and maintained goes through a

real world test before it is introduced on a wide scale.

A tiny city-state like Singapore, the smallest country in ASEAN, can never be self-sufficient in AFVs, which means the country makes everything it needs. This is because local demand is simply too small to justify manufacturing every type of armoured vehicle the SAF needs to move and protect its people while engaging hostile forces.

However, Singapore's push to build self-reliance in AFV technology gives MINDEF and the SAF options unavailable had we been forced to rely solely on off-the-shelf choices. The ability to design AFVs indigenously means new vehicles can be tailored-made to meet the specific needs of the SAF and its operating environment. It is a strategic advantage that results in specialised designs that enables the SAF to achieve mission success.

The Road Ahead

Projects Spider and Archer were game-changers. Experience leading these projects for the Singapore Army made Singaporean defence scientists and engineers eager to do more.

In time to come, ST Kinetics would earn a reputation as a maker of light to medium armoured fighting vehicles (below 40 tonnes in weight) with performance, ease of use and combat capabilities few could match.

Chapter Five

EXPLORATORY DEVELOPMENT OF AUTONOMOUS AND REMOTELY OPERATED VEHICLE

By Prof Lim Kiang Wee, Dr Javier Ibanez-Guzman, Dr Jake Toh and Mr Chan Chun Wah

In the 1980s, it was clear that the enormous intellectual capacity of the staff and students in our universities could make significant contributions in the development of technological solutions for the SAF. Finding a match between the research interests of the staff and the needs of defence required investment of the time of defence technology leaders and the leaders of engineering and science in the universities to meet and find areas of common interest.

Grumman International NTI¹ Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) Centre (GINTIC) was established in 1985 with the support of Grumman Aerospace, the manufacturer of the USN airborne early warning aircraft, the E-2C that was becoming operational in the RSAF. Under the ambit of GINTIC, Prof Khoo Li Pheng was one of the Nanyang Technological Institute faculty who had the opportunity to learn about the latest use of CAD/CAM in the aerospace industry from Grumman Aerospace.

The grand challenge of developing the technologies for autonomous driving from 1999 with the M113 APC as the platform created excitement that raised the level of research and development in GINTIC, and provided our defence engineers with the opportunity to learn from doing.

¹Nanyang Technological Institute – predecessor of Nanyang Technology University (NTU)

Preamble

By Prof Lim Kiang Wee, Division of Engineering and Technology Management, Faculty of Engineering, National University of Singapore

1999-2000 was a tumultuous period for the GINTIC Institute of Manufacturing Technology. GINTIC had been corporatised in 1997 following which the then Director, Dr Frans Carpay and its Board embarked on a growth strategy to position it as the "Fraunhofer-of-the-East".

Instead of relying primarily on research from the universities, GINTIC started to do longer-term upstream research in newly formed research divisions and launched a development division focussed on technology transfer to industry with full-cost recovery. It accelerated its headcount growth in the expectation that projects would follow. In the midst of this, it received a call for research proposal for Project Ulysses from DSTA.

Project Ulysses called for the development of a vehicle system capable of operating autonomously and remotely, day and night in natural environments. The vehicle system selected for the research was the M113 APC. The goal was to convert the APC into a drive-by-wire system, capable of vehicle following as well as autonomous driving in natural environments in daylight and for tele-operation day and night.

For the researchers at GINTIC, this was the opportunity of a lifetime. The project could bring together competencies developed in the research divisions. It could draw upon links already built up with university collaborators in Singapore, Australia and France. It could provide a focus for research. The demonstrator would allow the integration of ideas into a leading edge technologically advanced platform.

There was a snag. The proposed project was not an obvious fit with the core mission of GINTIC to support Singapore's manufacturing industry. The typical questions that would have been asked: What would be the economic value-add of this project? Could the young (and inexperienced) team deliver an integrative engineering project of this scale? Would there be additional competencies developed? Where would these competencies reside? Even more prosaic questions would include: Was this to be a project under the wings of a research division or was this to be a technology transfer project, in which case did the project meet GINTIC's "full-cost recovery" criteria? If this was to be a research project, would the then funding agency that oversaw GINTIC, the National Science and Technology Board (NSTB, the predecessor of the Agency for Science, Technology and Research (A*STAR)), approve of the project?

To complicate matters, the project did not have much visibility outside of the project team in the early stage of its development. Discussions relating to the project were also confined to a select group and the project did not feature in formal Institute presentations.

The question of NSTB approval probably never arose. As the Director of NSTB overseeing GINTIC then, I was not aware of the existence of Ulysses in its early stage and had found out about the project only after becoming the Executive Director of GINTIC (later renamed as the Singapore Institute of Manufacturing Technology (SIMTech)) when the project had already started. Nevertheless, the funds that came with the project were most welcome. They helped GINTIC meet the key performance indicators (KPIs) set by NSTB! Thus was born a "Skunk Works" project. The institute started the project as GINTIC and finished it as SIMTech.

This article assembles the recollections of some of the key players. The driving force for the project within SIMTech was Dr

Javier Ibanez-Guzman. His recollections and reflections follow. Dr Jake Toh provides a perspective for this ground breaking project and its follow-up from his perspective as an ST Kinetics engineer working on the project. From the funding agency, DSTA, the project officer, Mr Chan Chun Wah also provides a personal account. We conclude with some reflections on lessons learnt.

The Project Manager's Perspective By Dr Javier Ibanez-Guzman

Ulysses was a project sponsored by the Land Systems Division of DSTA between late 1999 and 2004. This is a personal perspective of the project that, with hindsight, demonstrated technological achievements that were well ahead of their time.

Today, 12 years after the project concluded, many of the technologies, concepts and ideas that emerged from Ulysses can be found in the disruptive technology that autonomous vehicles, together with connectivity, and electrical vehicles, represent for mobility and land transportation systems.

Autonomous Vehicles in Defence Applications

In the 1990s there was considerable interest amongst the armed forces of the NATO on the use of robotics technologies applied to land vehicles. The most notable was DEMO III in the US where an unmanned ground vehicle demonstrated different autonomous capabilities operating in temperate climates. Other NATO nations had similar programmes: Primus in Germany, a light air-transportable armoured vehicle with tele-operated and autonomous capabilities; Syrano in France, the same vehicle showing advanced tele-operated technologies.

In academia, the Robotics Institute at Carnegie Mellon University in the US was famous for the NavLab family of vehicles.

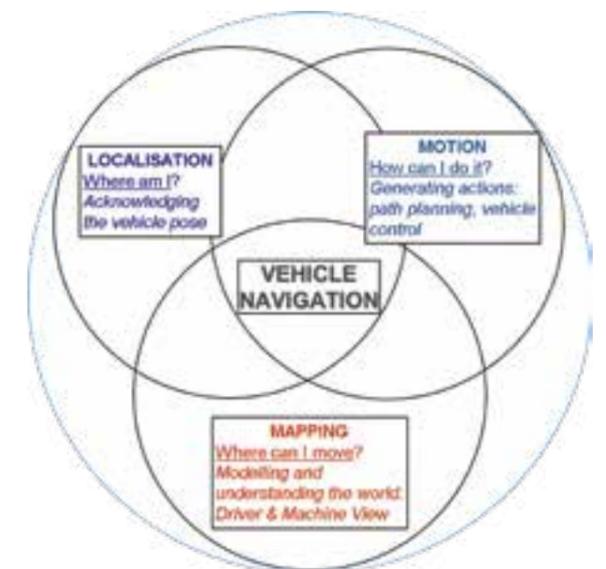
Technical Challenges for Autonomous Vehicles

Whilst computer vision applied to mobile robotics could be traced back to the mid 1960s, acquiring an image in real-time using the early Pentium PCs available to Ulysses was a challenge. The resolution available was sub-VGA and only in black-and-white. It was a major task to measure range and to

classify obstacles with a given height/volume criterion.

Localisation, that is establishing the vehicle's position with respect to a reference frame, was another challenge. The Global Navigation Satellite System (GNSS) as we know it was still under consideration. In those days, Selected Availability (SA) of the positioning signals from the US Global Positioning System (GPS) was enabled so accuracies lower than 20m were not easy to achieve with non-military equipment. Fortunately for Ulysses, the higher-resolutions GPS signals were available to the project team during the project.

In navigation which involves path planning and obstacle avoidance to reach the destination, most of the prior work had been performed for indoor robotics, for example, in the Hilare robot in France. The figure below summarised the technical challenges that were addressed in Ulysses.



Functions addressed by Ulysses for autonomous vehicle navigation

Information and Communications Technologies (ICT) were also limited in the early Pentium PCs, with communications limited to the 430MHz frequency as used in infrastructure projects. It was in the period just preceding

Ulysses that in the robotics community started to buzz about simultaneous localisation and mapping (SLAM). This turned out to be important for robotics mobility.

Before Project Ulysses – Project Diana

When I first joined GINTIC, there was a mysterious room in the second floor of the GINTIC building. Colleagues from that room made visits to an exotically named military camp and were returning exhausted by the heat and humidity but exhilarated by discussion on the difficulty of generating disparity maps to infer depth from stereo camera pairs, getting these maps in real-time at more than 2Hz, by non-linearities encountered by the vehicle controllers and the overall control stability. They were working on Project Diana, a proof-of-principle project for autonomous technologies. Diana explored the feasibility of developing local technologies for autonomous ground vehicles.

Competencies at GINTIC

My pre-Singapore experience was on construction robotics research, robotic-based assistive technologies for the disabled and the implementation of industrial robots in the factory floor. I had built wheelchairs, including one for a tetraplegic person, voice-controlled and with a safety system. Elsewhere in GINTIC, the buzz in robotics was around the Wing Inspection project, where a mobile robotic platform had automated the inspection of micro-cracks on the bottom part of wing of a fighter aircraft stationed at the workshops. The lead engineer for that was Dr Lim Ser Yong, today the Executive Director of SIMTech. Another high profile project was on the deburring of aircraft engine blades using a robotic cell, led by Dr Chen XiaoQi who went on to become a professor in New Zealand.

Other competencies that were to prove valuable to Ulysses included work on computer numerical control (CNC) machines

by Mr Shen Jian and Dr Gong Zhiming. In the area of vision there was substantial work on inspection machines for the semiconductor industry, bolstered by the arrival later of Dr Xu Jian. Ms Pooja Charturvedi provided programming capabilities for the detection of faults using the Matrox libraries. There was also work on software development for the optimisation of manufacturing processes by Dr Alex Tay. All these colleagues, with capabilities honed on other projects, became part of the Ulysses team.

None had prior experience with large vehicles.

At SIMTech, work on vehicles was triggered by one of the first seminars on Intelligent Transportation Systems in 2000 at the Nanyang Technological University (NTU) where I gave a presentation on my previous work and made contact with other speakers such as Prof Christian Laugier and Dr Michel Parent. I was given access to NTU's CyCabs (today called autonomous pods) that came from a collaboration between INRIA (France) and NTU. This was a vehicle advanced for its time and its creators, Dr Parent and Prof Laugier are pioneers in the field. We tele-operated the CyCabs in GINTIC car park using a RF modem and a PIC micro controller purchased



Tele-operated CyCab on trial in GINTIC carpark, circa 2000

from Sim Lim Square. We assembled our controller in an electrical distribution box, cut using the water-jet cutting machine at SIMTech.

Our colleagues from the mysterious Diana project, in particular Dr Andy Malcolm who was to lead the tele-operation part of Ulysses, began noticing our work.

Coming Together in Ulysses

Early in 1999, my research division director, Dr Fong Aik Meng told me to prepare a proposal for the automation of an M113 APC. He wanted me to be the project manager and to build a team. By then, almost the whole Diana team, with the exception of Dr Malcolm, had left GINTIC. I took on the challenge with enthusiasm without quite realising how important this project was to be for me.

We had our small all-terrain vehicle from iRobot (in the days before its hit product, the Roomba) painted in SIMTech colours. We were exploring voice-controlled tele-operation, laser rangefinders, cameras and radios with the iRobot vehicle. This was used as our prototype for Ulysses.



Different configurations of the platform used for tele-operation experiments

Developing the Proposal

Writing the proposal for Ulysses was a major endeavour. It was a painstaking process. I had to incorporate the vision and needs of the DSTA project officer and SAF officers. At the same time I had to find, choose and persuade not only the team members to join me, but also to seek the support of their group managers to release them from what was considered their core mission in manufacturing related R&D. Budgets and schedules also needed to be discussed and estimated.

At the same time I had to identify the technical gaps to be filled - we sought needed support of Dr Wang Han and others from NTU for the vision, perception and navigation functions, and Dr Sam Ge and colleagues from the NUS for the localisation and control functions. The transformation of the tracked vehicle into a computer-actuated platform or pseudo drive-by-wire was to be done by ST Kinetics.

I read all I could on the subject, in particular the work from Carnegie Mellon, from INRIA and from the Australian Centre for Field Robotics (ACFR) at the University of Sydney. Their work had a strong influence on Ulysses and on my career.

Several months elapsed after the early discussions. My prospective project members were being moved to other projects. Fortunately the contract arrived in the nick of time. Suddenly, I found myself with the largest project in GINTIC for the next three years, a young project officer and a 12-ton vehicle.

R&D Process

Ulysses was a contract between the Land Division of DSTA and GINTIC. The project officer from DSTA was Mr Chan Chun Wah.

We had a team with experience across a range of capabilities but not in autonomous vehicles.

The approach we adopted can be summarised as follows:

- The system was partitioned into a series of clearly defined sub-systems. Each subsystem had a leader. For those subsystems that we contracted external parties for, we had a SIMTech staff attached to the external party concerned to ensure there was technology transfer and increasing self-reliance as the project progressed.
- The conversion of the research vehicle into a computer control system by ST Kinetics was also followed closely, to learn how systems could be installed in an armoured vehicle. There were intensive brainstorming sessions during which SAF officers and our project officer worked out the fundamental user expectations.

SIMTech management recognised the need to support interactions with overseas centres of excellence. In the late 1990s most robotics conferences were centred on manipulation and indoor navigation. Attendance at conferences in field robotics, experimental robotics and the SPIE series of conferences provided our researchers with the needed perspectives. We accompanied SAF officers on visits to Germany and France, as well as centres of excellence in Australia and the US. From these visits, close interactions emerged with INRIA, Carnegie Mellon University and ACFR.

From the data acquired on-site from the initial trials using the perception sensors, it was clear that understanding of the physical constraints in jungle conditions was critical, so was the availability of a more accessible test platform than the M113. The opportunity to iterate between our theoretical models and the access to the physical systems was to prove important for the successful completion of the Ulysses project. This iterative approach had since then influenced most of our research.

The active participation of the project sponsor in defining milestones in the form of conventional systems engineering reviews such as the preliminary design review, the critical design review or the field operational test were very important for project management. They contributed to the discipline that yielded detailed reports that were used throughout the project and later on the field demonstrations.

Throughout the project, the research team was able to publish work whilst preserving the confidentiality constraints associated with the project. Several graduate students and interns from the local universities had also worked with the various researchers in the Ulysses team.

The Armoured Personnel Carrier

A M113 APC was not something that manufacturing-oriented researchers used often. When we went to inspect and to receive our unit, we began to appreciate the difficulties and constraints of operating such a vehicle. Its size, its powerful engine and its mechanical complexity were all at a scale beyond our prior experience. To help us get to grip with the complexity, we bought ourselves a couple of scale M113 models and built them over a weekend. This was very helpful!

Our DSTA project officer and I signed the temporary transfer document for the M113. We were responsible for it! Learning to work with this research platform was a whole new experience. There were considerable constraints on how we could incorporate experimental fixtures on the platform. ST Kinetics staff told us very patiently that we could not just drill where we needed to. An army vehicle needed to be clean as it entered the base compounds and for refuelling. It was a whole-team logistics issue to determine who in the research team was going to clean the vehicle!

SIMTech staff were trained to drive the vehicle and act as safety drivers.



Clockwise from top left:
M113 CAD model including sensor details,
the APC with the sensors outfitted
and demonstration with the driver's hands
outside the vehicle to prove that
the vehicle was moving autonomously.

The Pickup, Multipurpose Vehicle

Early in the project we needed an extra vehicle. Requesting this from our management was not easy. Upon authorisation, the whole team went out to buy the *blue pickup*. It was used to mount sensors, power generator, PCs and to transport materials and people.



The pickup configured with all the Ulysses
perception and localisation sensors

The team improvised rapidly. Dr Malcolm and Ms Jeanette Lim bought some aluminium profiles plus a drill. One day later, we had a framework where we could mount our sensors. We used homemade fixtures and lots of tape. It was simple and a far cry from the sensor platforms of today, built with CAD tools and by suppliers.

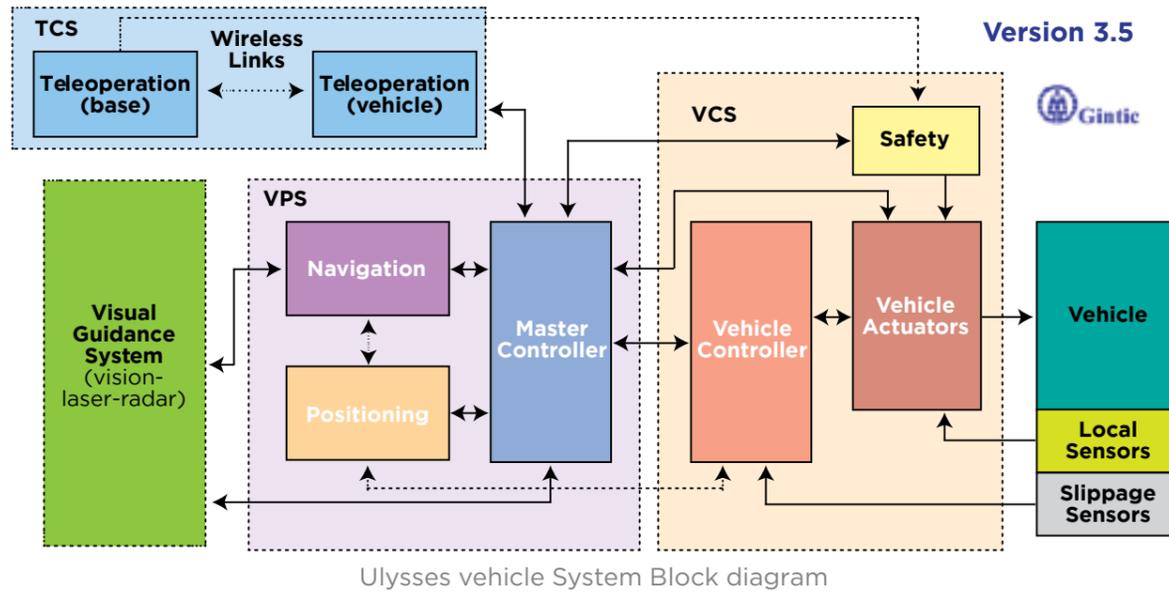
The Design

Each sub-system in Ulysses, comprising several modules, ran on a personal computer. The whole setup had to be installed at the rear of the M113 on a plate that reduced vibration. During the design phase we had to specify shock absorbers. At one point, mistakes on whether these were represented in parallel or series led to the support plate oscillating with the multiple computers on top. When the vehicle was to be cleaned or maintained, all the computers and sensors had to be taken out. The technical challenges are described in the following sections.

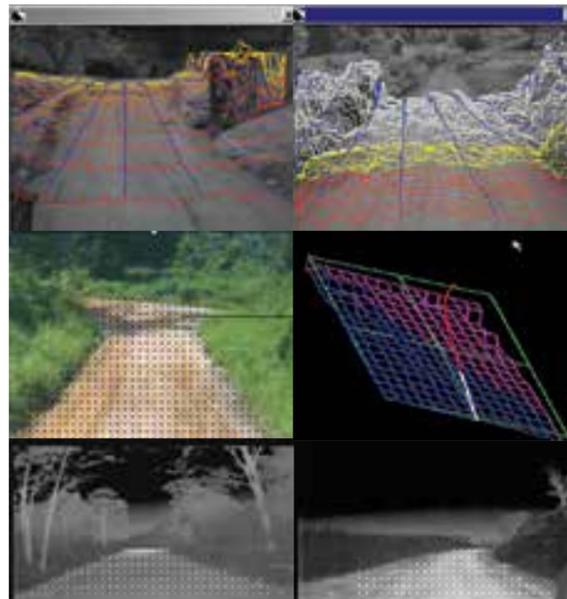
Perception

Prof Rodney Brooks, one of the fathers of modern robotics once said “perception is a hard problem”. In Ulysses, we only had single-line laser rangefinders used at that time mainly for indoor applications. There were three vision systems; a) stereo-vision based on the trinocular cameras by Point Grey. Disparity maps were created and from these, obstacles were detected. When we wanted to detect trenches, it proved difficult, b) road segmentation using colour cameras. The results from Ulysses were subsequently referred in the reference study for the US Army with regard to unmanned ground vehicle technologies². Even as we worked on Ulysses,

² Committee on Army Unmanned Ground Technology, National Research Council of the National Academies, *Technology Development for Army Unmanned Ground Vehicles*, The National Academic Press, Washington D.C., 2002.



Sandia National Laboratories³ commissioned a report from one of our collaborators on the state-of-the-art technologies in autonomous land vehicles. Today interest in road segmentation is very strong as the use of deep-learning techniques enables “semantic road segmentation” with much potential for facilitating situation understanding, c) the use of one of the first bolometer based infrared cameras to segment roads from the near environment at night and for tele-operation purposes. The results were very encouraging, and it was possible to segment roads with ease using as differentiator the temperature profiles. This was so effective that operators subsequently found that tele-operation of the M113 at night was easier than in the day.



Results from the passive perception systems: stereovision (top two), colour segmentation (middle left), slope analysis (middle right), and infrared images (bottom two)

After a visit to Dornier (today part of the Airbus Industries) and the demonstration of the Primus (German army autonomous vehicle), we brought in a 3D laser, a column of 16 sensors to sweep the terrain at 4Hz to provide a 3D map. Today, there is renewed interest in these sensors. It provides the 3D map used for autonomous driving.

³Durrant-Whyte, H., A critical review of the state-of-the-art in autonomous land vehicles, systems and technologies, Sandia Report, SAND2001-3685, Sandia National Laboratories, Albuquerque, 2001

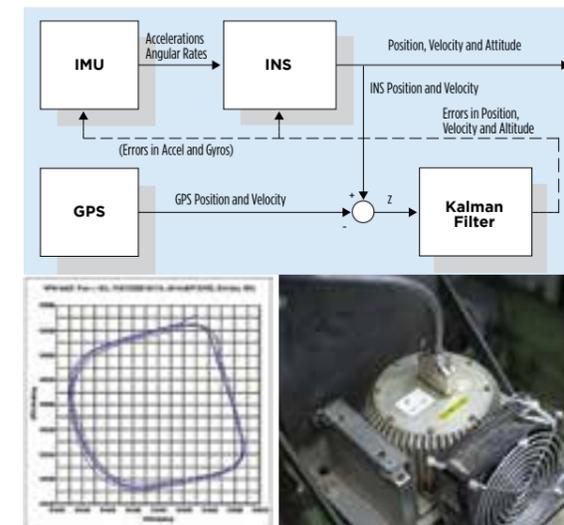
Localisation

Ulysses’ capabilities for localisation were based on waypoints given in WGS84 World Coordinates. The system needed absolute position. For this purpose, a GPS receiver, an inertial measurement unit (IMU) and a vehicle odometry were loosely coupled using

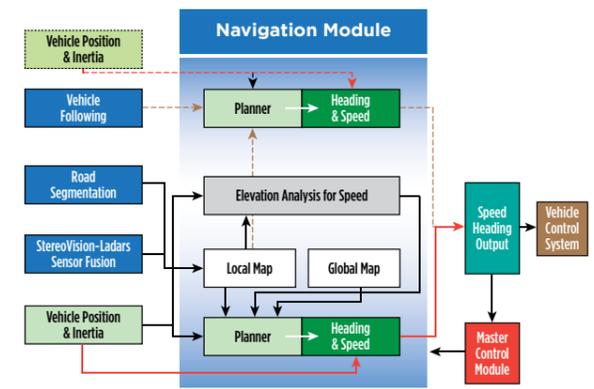
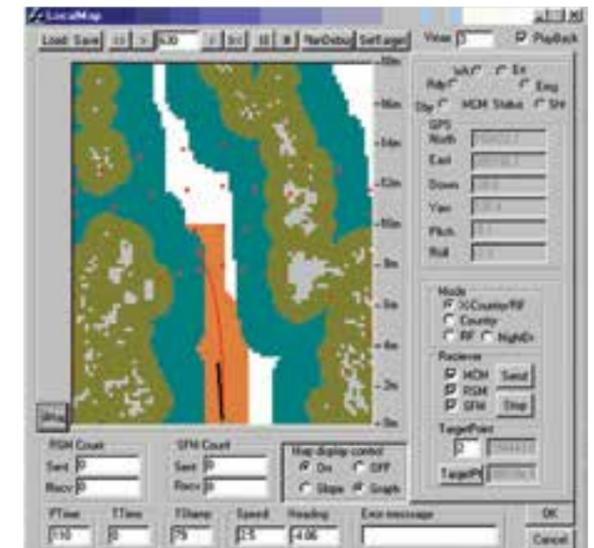
an Extended Kalman Filter. This sub-system was developed by ACFR in Australia and integrated and tested by the Ulysses team. It was an advanced system that taught us the difficulties of the localisation function and its importance for vehicle navigation.

An interesting hiccup: one day, the system stopped receiving GPS when the tele-operation system was switched on. This was a major issue as the vehicle could not be moved without knowing its pose (position and heading). We checked everything. When the problem persisted, the vendor for the GPS receivers asked the Ulysses team to look into the harmonics of the signals transmitted. Three weeks later, we discovered that our video transmitter for the tele-operation system was broadcasting at exactly the third harmonic of the GPS L1 frequency and had interfered with the GPS signal reception.

Today, SLAM is a well-recognised research challenge. My current research still addresses this challenge in autonomous navigation and when using low cost sensors. We, in Ulysses, were early contributors to this research.



The localisation system configuration (top) used and the results obtained (bottom left) on a vehicle that by its nature will vibrate very much during motion



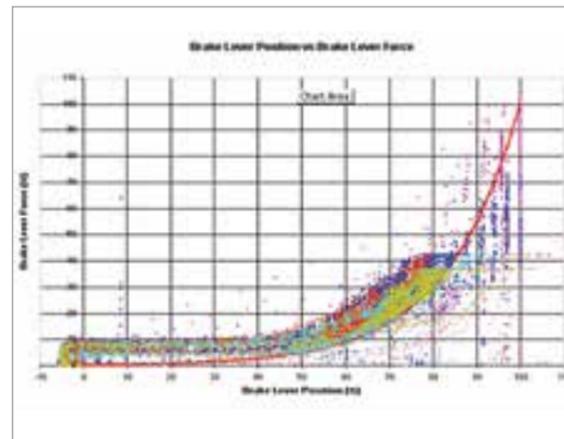
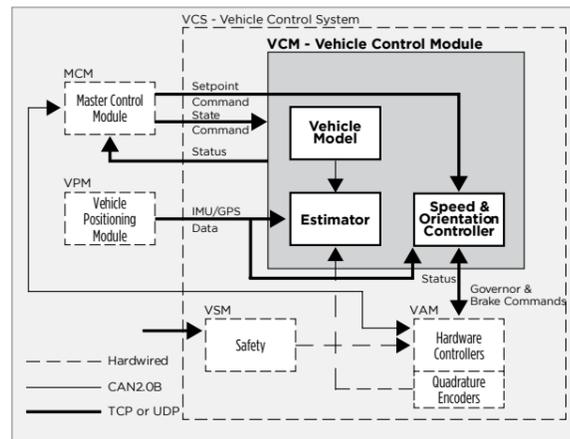
Ulysses’ visualisation path planner (top) and modular navigation system

Navigation

The navigation system allowed for the vehicle to go to a waypoint location whilst avoiding obstacles or following a preferred path. In a neat illustration of dual-use capability, Mr Shen Jian from the Ulysses team applied his experience in path planning of CNC machines for the implementation of the Ulysses navigation system!

Control

Controlling the motion of a 12-ton tracked vehicle propelled by a combustion engine having control levers that were entirely mechanical was a major task. Turning the vehicle required brake force to be applied



Vehicle controller configuration (left) and the non-linearity when one of the control levers was used to steer the vehicle

on the tracks via levers. It was necessary to actuate the commands electro-mechanically. This had to be done by inserting features that could only be fixed through brackets, as we were not allowed to drill holes into the APC hull!

The engineering of the electro-mechanical actuation system was done by ST Kinetics using a DOS-based PC, with algorithms implemented by Dr Jake Toh.

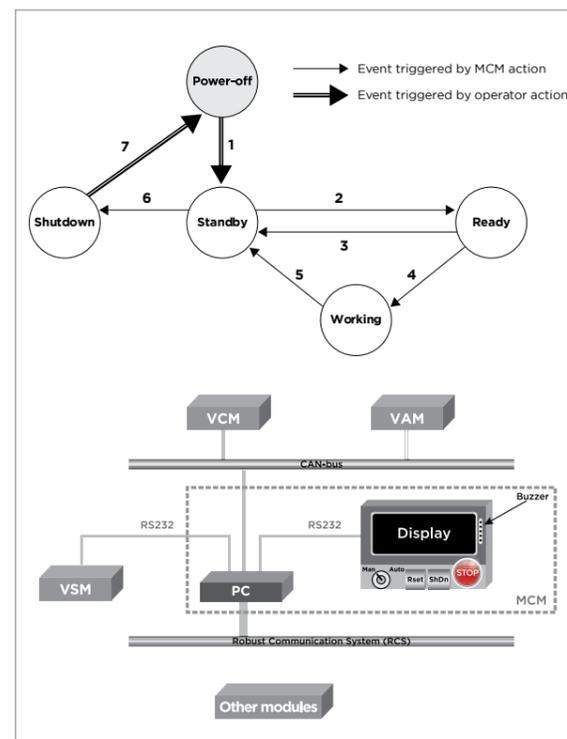
The vehicle controller was developed by ACFR in two phases. Three academics from ACFR arrived in Singapore from Sydney bringing sensors to characterise the vehicle dynamics and actuation systems. The controller algorithm was implemented bottom-up using a PC104 type computer. Even drivers for the encoder cards had to be written. Whilst advanced algorithms were first attempted, the team finally settled on an adaptive PID-based controller with very good results.

When the controller arrived from Australia and was installed on the M113, we thought that it would be helpful to lift the M113 off the ground to test the controller. Despite our best efforts at tuning the controller parameters, the system would remain unstable. We realised later that when the vehicle was suspended and the tracks were running freely, there was no load upon them, and the system dynamics

would be completely different. The vehicle was controllable where it belonged, on terra firma!

Supervisory Controller

The supervisory controller was the system that integrated all the functional systems together. It was analogous to a programmable logic controller (PLC) in the factory floor. To



Simplified finite state machine and supervisor hardware configuration

each functional system a finite-state machine was associated. This was controlled and monitored by the supervisory controller. It was possible to enable or disable the various functional systems, to reconfigure the system as it changed from manual to autonomous or to tele-operated modes.

The concept originated as part of the ‘joint architecture for unmanned systems’ (JAUS) sponsored by a community for unmanned ground vehicles. Today this is part of the Society of Automotive Engineers, USA Standard AS6057.

The introduction of the supervisory controller proved to be very useful, as the integration process was much facilitated as it was possible to control at will when the various systems were available and to monitor their operation using different watchdogs.

It is a matter of pride to the team that the first Google patent on Autonomous Vehicles⁴ referred to the SIMTech internal report⁵ on the subject.

Tele-operation

Another challenge was in attaining tele-operation capabilities for Ulysses when operating in tropical forests without the operator having a direct line-of-sight to the vehicle. The problem was compounded by delays in the transmission of data, and vehicle and operator response. There was a limited field of view for the camera that meant a pan and tilt unit to mount the camera was needed. Just locating the communications antennas on the top of the APC together with the GPS antenna was complex.

⁴L. Prada Gomez, et al. TRANSITIONING A MIXED-MODE VEHICLE TO AUTONOMOUS MODE, google Inc., US Patent N°. US 8,078,349 B1, 13th December 2011.

⁵T.C. Ng, “Master Controller of an Unmanned Autonomous Ground Vehicle”, STIU03/040/MECH, Retrieved on 26th February 2011.



Ulysses’ tele-operation console and command post

The M113 could be tele-operated during the day and at night. Surprisingly, operating at night was easier for the remote operators. The results were very encouraging. The vehicle could even be reversed. This part of the project was implemented entirely by SIMTech staff. Most of the techniques were prototyped using the small skid-steer robotic vehicle, the ATRV.

The console was to be single-man portable but only by Dr Malcolm. When transported by other colleagues, its weight would require two persons to carry.

Today, there is renewed industry interest in tele-operation. Some vehicle OEMs have large projects in this area.

Field Testing

The integration and testing of Ulysses was a challenge. The vehicle needed to be loaded onto a special truck by a professional armoured vehicle driver. For each test we needed a driver and a commander, fuel for our power generators and fuel for the vehicle. We had to pre-arrange access to an army training camp. The support from DSTA was essential for this task.

On multiple occasions as we were struggling with some tests, we found a large column of army personnel in full kit, waiting for their turn in the test area. Towards the completion of the project we had the SARS epidemic, which complicated our work.

The integration of sensors and tests were done at the site at high temperatures and 90% humidity. Computers did not like the environment. Neither did we. A typical day would start very early. We left SIMTech for each field test looking as if we were going for a picnic. By three o'clock in the afternoon everybody would be exhausted. We had to calibrate, characterise, configure and test the perception systems. The pitching of the vehicle as it moved, caused phantom obstacles to appear and disappear (known as pimples). The calibration of sensors and their alignment to a single reference frame was difficult given the vehicle configuration. Initially the vehicle was moved inside a triangle-shape trajectory to verify the operation of the software. This changed later to a test area with dense vegetation. At times our allocated trial space was changed due to army operational needs so we had to tune the algorithms again.



Logistics setup for trials and demonstrations

It was a proud moment for us that during the last tour, the vehicle went into an unknown zone and just via the waypoints found its way around the jungle. Everybody could see

the vehicle's progress but we were too excited to take pictures to record our achievement.

There were difficulties we discovered in the field. Occasionally, slope would look like an obstacle to the vehicle such that when it approached the slope it would grind to a halt. When the M113 moved in open space at close to 30 km/h, the gear-box would automatically shift. It was thus a challenge to compensate for the sudden change in dynamics. Delays in the overall system had to be considered carefully. At times, the vehicle would attempt to turn too close to trees, resulting in close encounters with the fauna. On another occasion, the accelerator got stuck and the vehicle went in circles until the actuating computer could be reset. Another challenge was the intensity of rain that was typical in Singapore.



Ulysses in autonomous operation, vehicle trajectories

Tele-operation functionalities worked very well. The vehicle could be controlled without direct line-of-sight, and could move close to the lake and climb slopes, etc. At one point we even had a trailer being towed under tele-operation. This was done successfully though reversing was not that easy.

We had some problems due to the idiosyncrasies of the lasers rangefinders. When the M113 was near the reservoir, it could suddenly turn towards it thinking that it was an empty space, to the horror of everyone in the research team.

Towards the completion of the project, we had to address vehicle-following capabilities as part of the contract. This was done in a very short period, and it proved that the system architecture was designed well. A new capability was incorporated using only software. The leading vehicle was the SIMTech van and the following vehicle was the 12-ton M113. By general consensus, I as the project manager had to demonstrate my faith in our work by driving the van.



Ulysses in vehicle following mode and system prototyping

The Demonstrations

The Ulysses team conducted several demonstrations to MINDEF, the SAF and DSTA. These included a demonstration on Ulysses' tele-operation capabilities in a very tight compound to then Chief of Army. A full demonstration of Ulysses' capabilities in tele-operation and autonomous operation

was also made to then Chief Defence Scientist Professor Lui Pao Chuen.

The Ulysses team also gave demonstrations of Ulysses' capabilities to several overseas groups. These included a French delegation of officers from the Direction Générale de l'Armement (DGA). Staff from the Thales group came to a workshop on the technologies. They were very impressed by the capabilities developed with the budget available. As a follow-up, the DGA invited a delegation from Singapore to a demonstration of Syrano, a light armoured vehicle under tele-operation which was developed by Thales⁶. At the demonstration, researchers from SIMTech were the only civilian guests.

Officers and staff from Dornier came to visit us. Given the strong electro-mechanical nature of our M113, they were very surprised by what was achieved with our vehicle. We were also invited to a demonstration of Primus, another light armoured vehicle built by Dornier/Daimler⁷. This was a vehicle guided mainly by laser rangefinders at high speeds operating in central European conditions.

A US Army Officer and the Military attaché were hosted by our sponsors. We demonstrated the vehicle operating under tele-operation control even in heavy rain.

Ulysses was also featured at an SAF Army event. The project was presented successfully to a full amphitheatre of dignitaries from the SAF.

⁶ Morillon, J. G., et al. (September 2003). SYRANO: a ground robotic system for target acquisition and neutralization. In *AeroSense 2003* (pp. 38-51). International Society for Optics and Photonics.

⁷ Schwartz, I. (2000, July). PRIMUS: autonomous driving robot for military applications. In *AeroSense 2000* (pp. 313-323). International Society for Optics and Photonics.

A Perspective from the Partners in Ulysses

Mr Chan Chun Wah, then Project Officer from DSTA

I was a fresh graduate just starting my career with the Civil Service in the year 2000, after serving my remaining NS obligation. I was looking forward to starting work in the then DMO, where I had been placed. I had wanted a career which had technical content, as well as significant managerial responsibilities. It was a lucky break that the Civil Service placed some of its returning scholars in statutory boards and not just in the ministries. The icing on the cake? There was a small project group in Land Systems, DMO, specialising in robotics. It was probably the only group outside of academia in Singapore who engaged in this topic. This, by itself, was exciting and appealed to the child in me. How about that, playing with “big boy toys” as a career?

Mobile robotics (with some form of autonomy) was still relatively new in the military, not considering the remote controlled explosive ordnance disposal (EOD) robots which have served the Singapore Combat Engineers well. The technologies concerned were mainly still in exploratory stage. The community was trying to find a structure to the solution. Therefore, funding was modest, for exploratory projects, and required efficient use of resources and finding the right partners.

Small budgets, however, did not mean that we did not think big. It was as big as a M113 APC, which we managed to borrow for this project with the help of our colleagues in the Army Weapon Staff Plans.

This was the beginning of Ulysses – an unmanned M113 with remote control and autonomous capabilities.

The A-team consisted of researchers from GINTIC and NTU, who provided the

technologies behind the vision and navigation, and engineers from ST Kinetics who provided the control and adaptation to the mechanics of the platform. The sponsors from the Army Weapon Staff provided the operational input. This was a typical ops-tech co-operation which succeeded.

Ulysses laid the ground work for technological focus for future developments, as well as helped the users to see where operational pay-offs could be reaped immediately, and where further technological developments were required. It was an important step in learning how to harness unmanned technologies. Because of Ulysses, future projects had considered aspects of unmanned technologies in manned vehicles.

Working on Ulysses was fun, to say the least. It started from computer modelling, to conducting trials in the field (sometimes at night in Lim Chu Kang training area), testing the vision and control algorithms, and culminating in the final acceptance test where the vehicle navigated by itself and avoided obstacles in the field.

All in all, we achieved a lot with a small team, modest budget and good team work. While we did not manage to enrol in the first DARPA Grand Challenge, due to participation rules, based on the achieved outcome we theorised that Ulysses would not have fared too badly!

Dr Jake Toh, then from ST Kinetics

The Ulysses project is a first in many aspects for ST Kinetics and me. During that time, ST Kinetics was not known for undertaking R&D projects. As the SAF was transforming itself into a 3G fighting force, the company knew it needed to keep pace with the changes and started to look beyond the traditional disciplines of mechanical, electrical and electronics engineering for its engineers. Fresh out of university, I was the first mechatronics engineer to be recruited.

I was in charge of “robotising” the vehicle in the Ulysses project. I had to create a Vehicle Actuation Module (VAM); essentially a drive-by-wire (DBW) kit to overlay the vehicle’s existing manual controls, as the vehicle manufacturer did not allow access to the actual vehicle subsystems we needed to control.

While the design of the DBW system was relatively straight forward, ensuring system safety was the real challenge. Even as a young engineer, it was immediately apparent to me that the DBW kit is a critical safety component for any unmanned vehicle. This is because it is the only mechanism by which the vehicle can be brought to a stop electronically. In my view, this was the true value ST Kinetics brought to the project. I was able to tap into the expertise within the company in designing safety critical systems, accumulated from developing the Bionix and Bronco AFVs. In addition to expert opinions, the framework and procedures that the company had were invaluable resources to the project.

One of the objectives of the Ulysses project was to use commercial-off-the-shelf (COTS) products to develop a proof-of-concept demonstrator. The intent was noble, but it added complexity to my work. I had to take equipment designed for use in a static factory environment and adapt them for use in a tracked vehicle operating in rugged terrain.

An example of how harsh the operating conditions were was that an amplifier failed during one of the trials when one of its capacitor’s legs snapped. This was due to the constant vibration it was subjected to while the vehicle was in motion. ST Kinetics had a lot of experience ruggedising electronics to MIL-SPEC, the gold standard for military grade equipment. However, to apply that to every piece of equipment would not have been economically viable for the project and defeated the purpose of using COTS equipment in the first place.

So, the answer was to do enough, but how much is enough? Nobody knew the answer and we embarked on a journey of discovery. We started with a best guess effort and slowly iterated towards an appropriate level of ruggedisation. It was an exciting time for me personally as we were pushing the boundary of existing know-how, even with something as basic as the VAM. The knowledge acquired was carried over to subsequent unmanned ground vehicle (UGV) projects that ST Kinetics worked on.

Twelve years after the conclusion of the Ulysses project, the genetic makeup of Ulysses still lives on the UGVs being developed by ST Kinetics. After the project, I served as the chief systems engineer to ST Kinetics’s first in-house UGV project. In addition, I also designed its DBW kit. Over the years, ST Kinetics has developed into an integral part of Singapore’s self-driving vehicle eco-system. Looking at the UGVs it has created, the link to Ulysses is clearly evident to those of us who were part of the Ulysses team.

Postscript and Reflections

Ulysses was completed with many technical achievements. These are summarised in Annex B. SIMTech submitted a follow-up proposal for a Ulysses 2 project. This was not successful. Nevertheless SIMTech pursued some of the technologies, participating in an R&D project with NTU on the feasibility of deploying an autonomous golf cart and in a collaborative project with NUS and Prof Oussama Khatib of Stanford University aimed at applications in healthcare and rehabilitation. With the conclusion of Ulysses, team members were redeployed to other projects.

Reflections by Dr Javier Ibanez Guzman

The results obtained in Ulysses were beyond expectations. The whole team bonded well and was very focused on the project even though we were all working within an

environment whose centre of interest was manufacturing. A strong ethos of cooperation emerged rapidly during the project. The rigour of thorough process reviews and the documentation mandated by our sponsors, DSTA, whilst unpopular with the researchers, was fundamental to the project progress.

Ulysses demonstrated the importance of a “man on the moon” type project. It allowed the team at SIMTech to make a technological leap in addition to yielding a high number of publications and new skillsets. One regret was that we could have capitalised on the results better - we should have submitted a higher number of patents.

It was difficult at that time to imagine the current interest in autonomous vehicles and the potential benefits to society. Singapore, given its topography, road networks, impeccable communications infrastructure and population, is in a unique position for the successful deployment of intelligent vehicle solutions. Even now, there is a strong link between the technologies developed in Ulysses and the applications that are emerging in intelligent mobility today, in particular with regard to vehicle safety, driving assistance systems for the elderly and autonomous vehicles. Ulysses can be counted as one of the pioneering efforts in urban mobility worldwide.

I remember Prof Lui Pao Chuen, ex-Chief Defence Scientist, expressing support for Singapore to participate in the DARPA Grand Challenge. Unfortunately, this was difficult due to the participation rules then. It must be recalled that the DARPA Grand Challenge in 2004 was a disaster as all robots broke down after only 12km out of the expected 240km. By contrast the 2006 event was a success and the rest is history. Today all vehicle OEMs are working on related technologies.

Reflections by Prof Lim Kiang Wee

Project Ulysses offers lessons for managing a research enterprise.

The conversations that led to Ulysses were possible only because SIMTech had already invested in individuals and in projects that developed the enabling capabilities, well before the idea of Ulysses was mooted. These were generic capabilities – as important to aircraft wing inspection or to turbine blade repair as they were to prove important for realising an autonomous APC. It illustrates a role of a research institute to nurture and sustain a spectrum of capabilities that can be brought to bear on emergent challenges.

It was equally important that the Ulysses team was ready to draw from a network beyond SIMTech – from the NTU research community in particular, with which the Ulysses team was most familiar, from NUS, as well as from international researchers in Sydney, Paris and Palo Alto. This network enabled important gaps in SIMTech's capability to be filled. In turn, the existence of a project such as Ulysses reinforced the engagement of the Singapore universities and international research communities with SIMTech and Singapore. It is no accident that the international collaborators such as Dr Michel Parent from INRIA, Prof Oussama Khatib from Stanford University and Prof Hugh Durrant-Whyte from Sydney University, all eminent in the field of autonomous systems, are all still involved in one way or another in Singapore research.

The requirement to build a demonstrator in Ulysses provided a clear focus for integrating skills and technologies. Initially by accident and later by design, SIMTech management provided benign support to the project. At that time, there was no clear idea on how the nexus between civilian and military research could or should be managed. So the decision to start



Group photograph of the Ulysses Team and its overseas visitors and collaborators after a field demonstration of the prototype; Dr Javier Ibañez-Guzmán and Mr Chan Chun Wah are the first and second, respectively, from the left in the first row. Dr Jake Toh is the ninth from the left in the second row.

the project was a local decision at SIMTech level, rather than at the corporate level. While it could be argued that the project was not central to the core mission of SIMTech, it was a great tool for demonstrating capabilities and for motivating staff. There was potential for glory within circumscribed boundaries and there were no obvious penalising trade-offs. It was easy to excite the researchers and to have the management team exercise a light touch in keeping an eye on the project.

Having DSTA as a deeply engaged lead user was critical. From the project sponsor's perspective, it was easy to measure success in a project like Ulysses. Nevertheless, DSTA set challenging specifications, facilitated trials and mandated a disciplined approach to documentation and project management. In Ulysses, it was a smart buyer with the ability to tap into a broad and latent talent pool.

The result was a project that delivered world leading technical outcomes that were a little

ahead of its time. Following Ulysses, there was no compelling economic or societal value case for the SIMTech to continue development of the technologies after Ulysses ended. It was not possible to participate in the DARPA Grand Challenge. It was only in October 2010, some six years after Ulysses ended and a decade after it was conceived that the demonstration of the Google autonomous car started to change international perspectives.

Fortunately, the ideas from Ulysses were not lost. Some resurfaced in ST Kinetics (*see Dr Jake Toh's story*). The architecture of Ulysses lives on in the work of the project manager Dr Javier Ibanez-Guzman at a large vehicle OEM, while in Singapore, there is still a direct line of researcher connections to the recent work of Assoc Prof Marcelo Ang in the SMART car. Meanwhile SIMTech continued to invest in developing related capabilities and these will now prove their value in new application areas such as logistics fulfilment and assistive robotics in healthcare.

Annex A. The Team and Partnerships

A.1 The Team

The following paragraphs include information on a colourful cast of team members:

- Ms Jeannette Lim, was the technical support officer at SIMTech, our right hand for all the electronics considerations and developer of the tele-operation system. Jeanette after Ulysses, despite being a young mother of three boys, went to obtain her Engineering degree from NTU.
- Mr Andrew Ng (Little Andy), a young support technician that ensured the logistics. The refuelling of the power generator was a spectacle; we needed to remind him that petrol is flammable. Andy went on to the police force.
- Dr Ng Teck Chew, development engineer at SIMTech, a very pragmatic person, developed the laser scanner and the supervisory controller. Our expert on laser sensors, designing one of the early forms of the Velodyne. Following Ulysses, I had the pleasure to co-supervise his PhD on vehicle-following at NTU in cooperation with Martin Adams.
- Dr Alex Tay, an ex-SIMTech staff who joined NTU, formulated the theoretical framework for the path planner. He had a good understanding of the physics of the system. Whilst a computer scientist he was able to provide the navigation system with the necessary flexibility. He worked with Prof Wang Han, also of NTU.
- Mr Shen Jian, was the SIMTech engineer who did the final tuning of the navigation capabilities. Later on he moved to work on shared control.
- Dr Andy Malcolm was originally from the Diana project at SIMTech. The tele-operation system he developed was always fully operational. His knowledge of optics was very valuable as with the proper lenses many image processing

issues could be solved. The documents were excellent. He was responsible for all the demonstrations involving the tele-operation capabilities.

- Dr Jake Toh, a young engineer at ST Kinetics. He applied himself thoroughly and succeeded by implementing the actuation control system. At the conclusion of the project, ACFR invited him to join them to pursue a PhD degree in related areas at the University of Sydney. Jake today is with the Ministry of Transport working on autonomous vehicles.
- Mr Leong Yew Kong the manager at ST Kinetics was fundamental for ensuring the transformation of the vehicle into a robotics platform. He is today very much involved in innovation projects at ST Engineering.
- Ms Pooja Chaturvedi at SIMTech implemented the road segmentation software. During the project she became a mum. We needed to remind her often that in her state, the installation of hardware was outside her scope.
- Dr Andy Shacklock entered late into the project. He had worked on the IR camera for autonomous navigation, He has built his own company, Projective Space, working today in related areas.
- Dr Peter Chen an ex-SIMTech staff who moved to the NUS was responsible for the supervisory control system.
- Dr Gong Zhiming, Mr Thomas Thng, Mr Eddy Lim and Mr Jiang Ting Ying are other colleagues that also worked in the project whose contributions were very valuable.

All the team members took particular delight in wearing our coveted bright Blue Polo with the Ulysses name and DSTA/SIMTECH written on it.

A.2 Overseas Partners

ACFR at the University of Sydney was responsible for the localisation and control

systems. Developments were done overseas with the complete integration done by local staff. Prof Hugh Durrant-Whyte was the main partner in cooperation with senior academics Prof Eduardo Nebot, Dr Graham Brooker, etc.

Annex B. Summary of Technical Achievements

- An M113 APC was operated autonomously and remotely in daytime and at night in natural environments.
- The vehicle demonstrated autonomous cross-country, road following and vehicle following functions, as well as non-line-of-sight tele-operation.
- Perception. Stereovision using a commercial trinocular worked well, and the concept is still being used. Issues like auto-calibration today remain a challenge. What was missing was object classification. There was a full understanding on the use of laser rangefinders. Today, this technology is coming in force and shall challenge many computer vision applications. Road segmentation was the result of follow-up work of an MSc thesis. This is of much interest as it is possible to perform semantic road segmentation to facilitate machine situation understanding.
- Localisation. The combination of signals from odometer, GPS and IMU in a loosely coupled manner was the state-of-the-art at the time. It demonstrated how technologies can be jointly developed with a team overseas. Similar solutions are found today in industrial products.
- Navigation – Vehicle Guidance. A unique achievement was its modularity; the planner could be used for different operating modes, and it included the elevation analysis to ensure the vehicle will not tilt. The main difference to what can be found today is that it does not use a priori information in the form of maps.
- Vehicle Following. By combining tracking, obstacle detection, localisation information and inter-vehicle communications, what

was attained is similar to what current research proposes. Vehicle-to-vehicle (V2V) communications is having a major push. Ulysses in this sense combined the technologies beyond what several vehicle OEM demonstrators can do.

- Supervisory Controller. This is a unique achievement which facilitates integration and also ensures the reconfiguration of the vehicle operation. Similar configurations exist in different driving assistance systems and autonomous vehicles.
- Tele-operation. Capabilities included camera control, remote monitoring and waypoint navigation using off-the-shelf components. A modular system which is similar to what can be found in similar defence vehicles. The knowledge was applied to a robotic water jet cutting demonstrator at SIMTech and a patrolling robot for homeland security applications.

INNOVATION IN COMMAND, CONTROL, COMMUNICATIONS AND COMPUTERS SYSTEMS

"The Army can make you an officer but only Signals can make you a commander since without communications, you cannot control; and without control, you cannot command."

LG (Ret) Winston Choo, former Chief of Defence Force and a Signal officer

The development of command, control, communications and computers (C4) systems was a critical component in the evolution of the SAF's fighting capabilities. Starting with limited electronic technologies left behind by the British and those procured from overseas, the DTC had, over the decades, built up an array of impressive high-end C4 capabilities. Many of these capabilities eventually became indigenous technologies and competencies in the DTC that have enhanced and will sustain the SAF's fighting capabilities into the future.

The engineering capabilities acquired in the early years laid the foundation that enabled the SAF's tech-savvy operational commanders to customise C4 systems to best meet their unique operational challenges and requirements. It has enabled them to efficiently organise their forces, to effectively train their regular and national servicemen, and to multiply combat power by swift orchestration and concentration of forces to where it counts most, when it is needed. To a great extent, this approach of iterative operation-technology integration achieved through the evolution of C4 systems has enabled a truly technologically advanced, integrated and networked 3rd Generation SAF.

This chapter first describes the evolution of large-scale C4 systems in the Army, and in the later sections, the integrated C4 systems for the networked SAF. It seeks to illustrate the innovative spirit of the SAF's commanders and defence engineers to harness state-of-the-art technologies available to meet demanding operational challenges. In the area of C4, the supply of technologies and resources alone would never be sufficient, and this was especially evident in the early days. The pressing need to build up a credible and capable force with technology amidst resource constraints inculcated a strong spirit of innovation and improvisation in the commanders, defence engineers and the Signal people. The Signal Formation with its people played a pivotal role in enabling closer ops-tech integration between the operational communities and the defence engineers, and was responsible in developing and operating the C4 systems in the field.

To succeed in the development of these complex systems that involved many sub-systems and people across military arms, the commitment of commanders during the project deployment stage was paramount, without which the project would have halted at the slightest technical glitches. Developing and sustaining C4 capabilities required long-term commitment by the senior leadership in MINDEF and the SAF. The stories and statements made by the SAF commanders at various important occasions illustrated within this chapter served to demonstrate their vision, resolve and willingness to learn new technologies, and push ahead with challenging initiatives. This continual commitment by successive generations of SAF commanders over the decades was the most critical success factor in this journey.

Laying the Foundation (1965 - 1980)

The history of the SAF C4 began in 1966 with the formation of the 1st Signal Corps and the Communications and Electronics



C&E Department and 1st Signal Corps on Parade in 1966



(C&E) Department, one of the departments in the General Staff Division to build and provide the communications and electronics capabilities for the SAF. The first Chief of C&E Department was then Superintendent Michael Thoo, who was in charge of the Police Radio Division. He reported directly to the Director of General Staff Division, Mr Tan Teck Khim, and was tasked to lay the foundation for the Signal Formation. In this early stage, it was realised that a formal training system was urgently needed to support the growth of the SAF. Thus, the SAFTI Signal Wing was quickly established in the same year.



Official opening of SAFTI Signal Wing by Dr Goh Keng Swee, then Minister for Interior and Defence, in 1967

In 1970, recognising the need to deal with complex command and control (C2) issues in a fast expanding SAF, the C&E Department was re-designated as Headquarters C&E (HQ C&E).

This was a trying period of limited equipment and manpower. A tremendous amount of initiative and courage was required and the

pioneer Signal officers and non-commissioned officers rose up to the challenges. Recounting the challenges faced by the General Staff Division and HQ C&E on the development of SAF C4 operational doctrines and systems, former chief C&E Officer COL (Ret) Chew Bak Khoon said, *"All of us were no experts. When the advisor gave us advice, we did not know whether it was applicable to the SAF. So we used to have long marathon discussion sessions thinking and studying other countries' doctrines, as we had no experience. Nobody could tell us what to do. In the end, we took a leap of faith and conducted operational and technical trials so that we could learn and determine what was most suitable for the SAF."*

Like most of the SAF's equipment then, the radio equipment initially used by 1 SIR and 2 SIR was from the UK. Many of them were bulky and heavy, and thus unsuitable for smaller-built Asians. While they served the SAF's basic needs well, they did not meet many of the SAF's operations requirements. The equipment also had many limitations such as reliability, and the small number of Signal people who operated them often had to improvise electronic components to overcome the limitations. To support this effort, COL Chew Bak Khoon established an electronics laboratory in HQ C&E to conduct technical trials of new gadgets produced by in-house technicians. Reminiscing the joy he had trialling the newly developed gadgets, he shared, *"In those days, I personally spent long hours in the lab and it was a fun and meaningful time of learning with my C&E technical engineers."*

Often, we would go downtown to buy electronics components and fabricate "boxes" for operational use. This period lasted for about a decade until such time where the more state-of-the-art radios were available to us."

The "Big Brother" – PRC 6 Combat Radio

The first handheld and short-range Very High Frequency (VHF) combat radio used in the SAF to provide communication between forward elements at the battalion level was the US-made PRC 6. In those days, as there were no mobile phones, the PRC 6 was a useful mobile communications solution and was thus widely used for administrative and security purposes. As the need for a longer range and more secure radio set became apparent, the PRC 6, fondly known as the "futuristic" mobile phone, was phased out in the late 1970s. LTC (Ret) Foo Jong Ai, former Chief Signal Officer recalled, *"While the radios served us well, we recognised the need to enhance the security of our radio communications. Hence, advanced combat radios with electronic counter-counter measures were phased in to prevent people from eavesdropping on our conversations."*



PRC 6 Combat Radio

AN/PRC 25 (Army/Navy Portable Radio Communication 25)

The most advanced man-portable radio used by the US Army then was the AN/PRC 25, which weighed less than 10kg and was

deployed in Vietnam in 1965. In Vietnam in 1965 and some 33,000 AN/PRC 25 radios were deployed in 1968. This radio was selected by the SAF. With the increase in the number of combat units following the UK's decision to withdraw all troops from Singapore by 1971, local manufacture of combat radios became economically justifiable. An improved solid-state version, the PRC 77, was introduced into service in 1975. Approval was obtained from the US for the production of combat radios in Singapore in a joint venture between Tadiran and CIS. On completion of the production of radios for the Army, Tadiran pulled out of the partnership and CIS began indigenous development and production of electronics equipment for the SAF.



12 Series Radio

The build-up of higher level headquarters and armoured units led to the need for vehicle mounted radios with longer ranges than the PRC 77. Thus, the VRC 46/47/48 radios were selected for infantry units and the VRC43/12/44 radios were fitted in armoured fighting vehicles.

The Radio Relay

To support the increased communications needs to command and control larger forces, single channel radios were insufficient. The AN/GRC 103 multi-channel radio relay (R/R) system was introduced to the SAF in the late 1960s. The R/R system enabled multiple users from one location to talk to multiple users at the higher headquarters simultaneously. To enhance the R/R system's mobility in supporting the manoeuvring forces, the Signal

people and C&E engineers worked hand-in-hand to install the systems on Unimog vehicles with shelters that were well-suited for the local terrain. The R/R system worked in the Ultra High Frequency (UHF) band, and with proper siting, could communicate with other stations up to 50km away.



AN/GRC 103 multi-channel radio relay system

In the mid 1980s, the fleet of Unimog vehicles was upgraded by the defence engineers to be capable of supporting 30 communications channels between the brigade HQ and the division HQ. The R/R Unimog vehicles were connected to the Mobile Patching Centre (MPC) that was operated by signallers, and it served as a switching centre connecting line callers to their destinations manually. Due to the large number of patching cables the MPC had, it was jokingly referred to by signallers as the "big sotong¹". The successful deployment of the R/R system was accredited to the defence engineers who integrated the wide range of equipment from various vendors to fulfil the SAF's philosophy of integrating the best combination of equipment from different vendors to meet our unique needs at the least cost.

¹ Sotong: Malay word for squid.

That being said, the R/R system was not without teething issues. MWO (Ret) Christopher Noel recalled that the systems were prone to over-heating due to Singapore's tropical climate and the lack of effective ventilation when installed in the Unimog vehicles, which resulted in frequent communications breakages. This issue was so severe in an overseas exercise that he and his teams had to remove the radio systems' air filters and use wet sponges to cool the systems continuously, just like taking care of kids when they have a fever! Such an issue and solution would be unthinkable by today's standards.

In addition, for any large-scale exercise, the communications challenges and obstacles that the Signal people had to overcome were always real – the communications system was either working or not. The pressure to deliver was often intensified as the exercise typically involved a large number of "reservists" (now known as NSmen) in the command posts, and entailed the testing of new army operational concepts. Through this, signallers were forced to prepare for possible failures and develop mitigating solutions beforehand. The challenges faced then were further exacerbated by the rapid introduction of new technologies in the 1970s.

Many a time, the Signal people had to attune and assimilate themselves to the new technologies quickly to support the exercises successfully. It was through these challenges that signallers developed a range of improvisations - a set of "doctrines and standard operating procedures" to think out-of-the-box during routine training sessions. This inculcated an innovative spirit in signallers, and allowed them to bring the lessons learnt back to the planning room to co-innovate solutions with defence engineers, and forge a strong symbiotic relationship between the operations and technology communities. This is just one of the many stories on how the ingenuity and adaptability

of the Signal people and defence engineers resolved system issues that arose in the field.

The Evolution Begins (1980 – 2005) – From Analogue to Digital

Building on the firm foundation laid by the pioneers in the early years, the next generation of Signal leaders and defence technologists guided C4 developments with courage and ingenuity to phase out analogue and phase in digital communications and C2 information systems (CCIS), and elevate the command, control and communications (C3) systems to C4 systems.

In 1977, HQ C&E was awarded the State Colours and Regimental Colours, and in 1982, it was renamed as HQ Signals. In 1986, the Joint Communications and Electronics Department (JCED) was also created to strengthen the SAF's capability in engendering cross-service C4 developments. The first Head of JCED was Dr Tan Kim Siew. This was a period where the commitment and innovative spirit of the commanders, Signal people and defence engineers were called upon to overcome more complex challenges. Exercising large-scale C4 systems became a norm, and it enabled swift and effective implementation of CCIS, eventually making possible the integration at the SAF-level across the Services.



HQ C&E awarded the State Colours and Regimental Colours in 1977

Meshed Trunk Communications System Network

One of the most notable advances in the 1980s was the conception, development and operation of the Trunk Communications System (TCS). The meshed TCS network replaced the point-to-point R/R system, and radically altered the landscape of tactical communications. It provided the necessary C4 infrastructure support for the new operational doctrines of the Combined Arms Division. It was also a time where the Signal Formation, in particular the Signal battalions, underwent transformation in organisational structure, operating doctrine, procedure and training to better operate the new system.

Developments for the TCS were initiated in 1982 under the leadership of COL (Ret) Lai Seck Khui, former Chief Signal Officer, who organised a team to look into the feasibility of upgrading the R/R system with the latest advanced technology to support the Army's new operational concepts. He recalled, *"The TCS came about when the SAF decided to modernise itself. There was a change of emphasis from jungle training to conventional warfare, and a big shift from close combat to large scale manoeuvre operations with masses of soldiers equipped with hundreds of radios, all communicating with one another on a single integrated network. The TCS acted like a central nervous system, conveying vital information through its communications channels to synchronise all war-fighting elements into one cohesive force, and allowing the use of facsimile when the rest of the world was still using telex machines."*

In 1987, then LTC Ng Eng Ho took over the reins from COL (Ret) Lai and saw through the procurement of the new equipment such as the GRC406 Radios. The system was later successfully fielded by 3rd Signal Battalion in an overseas exercise in 1989. In the following year, under the leadership of LTC (Ret) Foo Jong Ai, then Chief Signal Officer, the TCS was inaugurated during the Signal Silver Jubilee parade on 1st March 1991.



Then Chief of Army, BG Ng Jui Ping at the inauguration of the Meshed Trunk Communications System

It was a significant achievement by the Signal people and the defence engineers who implemented the complex C4 systems, which comprised numerous sub-systems that were supplied by different vendors. It was an era where systems integration capability was built up. Through the project, defence technology departments and agencies gained valuable learning experiences. This enabled them to later develop and grow into a critical part of the DSTA that we have today. After much detailed planning and many trials, the TCS was fielded for the first time by the 3rd Signal Battalion to support an overseas exercise in April 1989. With its success, the TCS was officially commissioned in July 1990 by then Chief of Army, Brigadier General (BG) Boey Tak Hap.

With the TCS, mobility increased. Like a mobile cellular network, it provided tactical users with communications in the field through the nodes (base stations). In the process, new signal doctrines and processes were developed and trialled on-the-fly. In many exercises, two C4 support groups were formed for different purposes. One was tasked to operate the system designed for supporting the exercise, and the other to analyse the system's technical performance with the defence engineers. Together, the groups sought to optimise the system for increased performance and efficiency, to better serve the

users. The meshed web of inter-nodal links also added redundancy through switching and provided alternate pathways between HQs. This remained a key principle for subsequent C4 developments, to ensure reliability and resiliency of the SAF's C4 systems.

The Innovation in the TCS and the Split-Nodes

COL (Ret) Yun Ta Chun, former Chief Signal Officer, recalled that when the TCS was first introduced, there were four trunk nodes. In an advancing scenario, one or two trunk nodes were always in transition to the new location, leaving two to three trunk nodes to provide the backbone connectivity between the Division and Brigade HQs. The limited number of nodes presented a challenge in the TCS as the node locations were not able to support the dynamic nature of Division's manoeuvres and the rapid deployment of Brigade HQs. To create more nodes would mean more cost for the SAF; ingenuity was therefore required to work within resource constraints.

To overcome these constraints, COL (Ret) Yun led extensive discussions with the supplier, and their hard work finally paid off when they found an out-of-the-box solution. By reorganising existing TCS nodes with the employment of the split node concept, and by adding an additional switch in the node to support more radio links, the four nodes expanded to become eight nodes. This was a major low-cost innovation that greatly contributed to solving one of the critical issues in the system reconfiguration. Even up till today, this operational concept is still being utilised as it is resource-efficient and operationally effective. At the same time, the defence engineers also worked with the Signal people to derive the theoretical basis for TCS network connectivity and redundancy using network flow and graph theories to better assess the impact of communications failures.



Trunk Communications System on parade in 1991

The split-node concept represented the resourcefulness and tenacity of our people to overcome the odds to get the job done. Then MAJ Lee Shiang Long, CO 3rd Signal Battalion said, *"The development would not be possible without the very strong support given by the operational commanders at various force echelons, and the commitment from the Command, Control, Communications and Computers Systems Organisation (CSO), and its technical leaders and engineers. The engineers worked tirelessly, day and night in the fields with us (Signals). In many situations, they continued to work hard despite the lack of rest, and had to sleep where they could in the field, especially during overseas exercises."*

Five-Minute Land-Rover

The five-minute Land Rover was another product of ingenuity by the Signal people. It was a result of unorthodox improvisation by then MAJ Yun Ta Chun, during his tenure as S3, 3rd Signal Battalion. He was chided by then Division Commander, BG Patrick Choy, for the inability of the Division's tactical Unimog to keep up with the Land Rovers. He decided to prepare a vehicle that could keep up with the Land Rovers and set up communications in five minutes (instead of 30 minutes). The notion was preposterous at that time but then MAJ Yun meant his words. With his S4 and OC, they worked on the improvisations: transferring equipment from the Unimog to the Land Rover, remounting

the antenna on the Land Rover, and doing away with the traditional mast. One week later, he demonstrated his team's new creation to BG Choy. BG Choy was so impressed that he wanted the new creation to be fielded in the next overseas exercise, and it continued to be used in subsequent exercises.

Sparking a Mindset Change - Command and Control Information System

The beginning of the CCIS in the Army was an initiative mooted back in 1983. At first, there were discussions on whether this should be developed by the Signal Formation, since they were the subject matter expert in the field of communications and electronics, or G4, the Logistics Formation, being the most advanced at the time with their computerisation programmes for many logistics functions. However, it was finally decided that a new branch be set up in G5, the Plans Department of the Army, to oversee the development of this new capability where the experiences could subsequently be applied across the Army. It was placed directly under the watchful eyes of then Assistant Chief of General Staff for Plans (ACGS (Plans)), COL Lim Neo Chien. He also oversaw the development of the General Staff Office Automation (GSOA) System, involving the first transition from manual typewriters and physical dispatches to the computer keyboard and instant email transmission.

The CCIS Operational Masterplan

Later in 1985, a major CCIS project, the CCIS Operational Master Plan (OMP), was developed under the guidance of then COL Lui Pao Chuen and COL Lim Neo Chien, and then Chief of the General Staff, LG Winston Choo. A full enterprise architecture study was used to completely break down and understand all the processes and data entities that weaved through the entire fighting force, and reorganise them efficiently in order to attain shortest decision cycle time at all levels. The study not only provided clarity on how

to design the CCIS system, it also allowed the system to go further than the mere automation of existing processes through the usage of computer software. It also provided a platform for the various project managers to understand the operational requirements better, and to ensure that the projects did not go off-tangent during development.

Implementation of the CCIS

In 1994, the Signal Formation was handed the responsibility of implementing the CCIS systems for the Army. Led by then Commander 3rd Division, BG Han Eng Juan, and supported by the G3, LTC Tan Huck Gim, and then CO 3rd Signal Battalion, then MAJ Wong Meng Keh, they developed the operating procedure for the first CCIS system for the Divisions. With CCIS, the commanders adapted to the new technology and developed new operational processes and doctrines to better harness the CCIS as a force multiplier. They started using electronic overlays to draw on digitised maps.



Traditional way of operational planning using hardcopy maps and overlays

The introduction of CCIS in the Army transformed the way it operated. Information exchanges between the division and brigade HQ were made more efficient and effective with the exploitation of digital dissemination. Face-to-face briefings were conducted more expediently and effectively since the operations order by the division HQ could be sent to brigade HQ, and the brigade staff

could read and conduct preliminary analysis beforehand. The time required to complete the decision cycle was also reduced. The experiences gained and lessons learnt laid a firm foundation for future developments. Most importantly, it sparked changes in mindsets and seeded new ideas for the future. It was in view of these new ideas that then Commander 3rd Division, BG Ng Yat Chung said, *"The arena of war has changed exponentially since the dawn of the information age. Information is the enabler of the new warfighting system. Whether one likes it or not, the information age is already underway. The new CCIS would revolutionalise the C2 systems in the Army."*

With the strong support from Commander 3rd Division, the Division Chief-of-Staff, then COL Lee Ee Bek, and the then G3, LTC Yeo Eidik, as well as the ops users in the Division HQ were brought together with the defence engineers from CSO led by Mr Teo Chin Hock, and the Signal people. SSG Toh Cheng Seng, a CCIS system administrator then, remembered that two 21-inch monitors that looked more like televisions were necessary to enable digital maps to be viewed at a high resolution, which were displayed on large ruggedised monitors. Then LTC Yeo Eidik jokingly said, *"We needed cranes to move the 1st generation CCIS computers as they were so heavy and huge. Today, we have laptops and notebooks carried by hand."*



The 1st Generation CCIS being transported by crane

Improving the CCIS

To enable digital transmission for the CCIS, the digital packet switching technology was introduced into the TCS to make it data capable. Then MAJ Lee Shiang Long, CO 3rd Signal Battalion, recalled that a series of DIGILINK exercises were conducted by 3rd Signal Battalion and a group of defence engineers across Singapore prior to an important overseas exercise to evaluate the performance of the digital packet switching system. The exercises were designed in 1997 to systematically test and measure the system performance with respect to all kinds of data transmission parameters such as packet sizes, transmission protocols, and database and transmission delays. Through this, engineering graphs were plotted to derive the optimal system configuration.

While the multi-channel radios in the TCS were enhanced to enable data transmission, the challenge of transmitting large data and graphic files across the division and brigade HQs via wireless communications of limited bandwidth persisted. During that time, the operation orders were written using commercial software that was designed for transmission in wired communications using TCP/IP protocol, and were not bandwidth-efficient. To transmit a text document, the software would require three to five times the actual bandwidth to capture the formatting of the texts. Furthermore, large graphic files of the picture of the operational plan comprising various military symbols were also required to be sent. The Signal people, familiar with the operational content, and the defence engineers came together to meticulously filter out the essential information and remove the text formatting, and even created a new way to represent the military symbols more efficiently in digital forms. Through their painstaking efforts, the transmission of operation orders and operational plans across the HQs was eventually made feasible.



The 1st Generation CCIS

Involvement of the National Servicemen

Supplementing the efforts by the defence engineers and Signal people in overcoming the bandwidth limitation were the NSmen. COL Fong Yat Beng, who was former S3, 3rd Signal Battalion recalled how the NSmen were able to contribute in a significant way as they were tech-savvy and many were polytechnic graduates with electrical and electronics diplomas. There was a team of NSmen who developed a new File-Transfer-Protocol, which enhanced the speed and reliability of file transfer. This made the CCIS significantly more effective in transferring digital information over wireless communications, even though the communications was designed for relatively static command posts.

Besides the challenge to overcome bandwidth limitations, there were also two competing technologies in the market at that time - the UNIX operating system and the WINDOWS operating system. The original decision was to exploit the more matured UNIX operating system during the procurement process. However, during the project implementation,

about two years after the decision was made, the WINDOWS operating system gained faster speed and wider acceptance. As such, BG Ng Yat Chung opined that a parallel experiment should be run for the WINDOWS system. Then MAJ Lee Shiang Long initially feared that it would further thin down the already stretched resources from implementing the UNIX system. However, he could not refute the fact that the WINDOWS system was becoming more user-friendly and was beginning to dominate the market, and it would be easier for NSmen who had limited training time to assimilate the new system.

Again, the success of the experiment was accredited to the defence engineers who accepted the challenge and improvised a parallel WINDOWS-based CCIS using the same servers, networks and cables for the UNIX-based CCIS. In parallel, 3rd Signal Battalion was reorganised to support the parallel experiment. With the two systems operating side-by-side, a meaningful comparison of the technical performance and user-friendliness could be done. Through this, it showed that the ops-tech project team was capable of understanding the technology trends, and adapting and managing complex projects in the challenging operational environment.

Operationalisation and Deployment of the CCIS

Although there were limited opportunities to test, evaluate and adjust the new operational concepts and systems of the CCIS, the commanders, defence engineers and Signal people worked vigorously to operationalise the CCIS, and their efforts prevailed. BG Milton Ong recounted his experience when he was formerly an OC in 3rd Signal Battalion, *"We only had nine months before a major overseas exercise. We had so many exercises – almost once a week. The schedule was extremely tight. We needed to operationalise CCIS equipment within a few months of their delivery and get them ready for one of the biggest overseas exercises. It was a tremendous challenge but we made it."*

BG (Ret) Lee Shiang Long remembered that the commitment of the division HQ and its then commander, BG Ng Yat Chung, to the goal of deploying the CCIS was instrumental to its successful deployment. There were occasions where the entire division HQ was not able to function due to the longer time needed to set up the servers, leading to tremendous pressure to go back to the old paper map. However, the Division Commander insisted on waiting for the servers to be configured by the system administrators before conducting planning on CCIS. With the deployment of the CCIS, it was necessary for the Signal people to be trained to keep up with the technology. Some regular Signal specialists such as then 1SG Joseph Lim, then 1SG Lim Chong Han and then 1SG Chan Guan Seng went on to attend diploma courses in engineering. Among them, then 1SG Joseph Lim received the top graduate award in his cohort, and subsequently pursued a degree part-time. In addition, operational commanders at all levels were keen to learn new technologies while the project was being implemented. It was a time where commanders, defence engineers and Signal people learnt together.

Operational Challenges of the CCIS

One of the operational challenges when deploying new systems in overseas exercise was the potential of frequency interference with the host country's frequency usage. In some countries, the rural areas were served by microwave radios, and these transmissions were powerful as they were required to traverse long distances and overcome terrain obstacles. When the signal nodes were deployed, these pre-existing transmissions frequently interfered with the signals and caused communications failures. Eventually, the defence engineers and Signal people came up with an improvised solution. Before major overseas exercises, the Signal people would conduct communications trials to test parts of the plan and check the accessibility of the locations. Beyond the normal tasks, the Signal

nodes were asked to do “frequency scanning” during trials. Scanning was done using radios, antennas were rotated 360° and the signal interferences were recorded at various frequencies. This makeshift solution enabled the signal planning to consider pre-existing transmissions and thus minimise interference during exercises. Defence engineers also helped to develop frequency interference software for planning purposes, which involved calculations on the range of possible interferences such as multi-path, harmonics, inter-modulation, and RF noise.

The scale of the exercises also imposed severe constraints on the radio frequency management. Then SSG Seah Chiong Lok, who operated in the Systems Control (SYSCON), 3rd Signal Battalion, shared their satisfaction gained despite the challenges faced, *“The allocated frequencies were minimal and close to one another. It was tricky because we had to reuse frequencies. A lot of demands were also on the nodes because any slight node displacement on the ground would result in a frequency interference that could affect the entire network. Eventually, we managed to achieve “green” status (comms through) for all the radio links!”*

BG (NS) David Koh, former Chief Signal Officer and Head, Joint Communications and Information Systems Department (JCISD), also recalled, *“Every Signals exercise has a very high degree of reality because the terrain challenges and obstacles faced are always real. The most challenging nature of our work is that every exercise of ours is akin to a live firing. And our live firing is public. If there’s no communications, there’s no communications. You can’t bluff it. So, the nature of our work is that people see our real capabilities, and it is very, very public.”*

Besides 3rd Signal Battalion, 9th Signal Battalion which comprised mostly NSmen, also brought and deployed the CCIS for overseas exercises to operationalise it across the whole Army. MWO (Ret) Eddie Foo reminisced that filling many containers with communications

equipment was a mammoth task due to the limited manpower for the preparation. He stated that his most fulfilling moment was when then Commander 9th Division, BG Lim Chuan Poh patted him on the back and congratulated him for a job well done at the end of the exercise.

2nd Generation CCIS

Rapid advancements in information technology at the dawn of the new millennium led to commercial IT hardware developing at an unprecedented pace, spurring the development of the 2nd generation CCIS. Led by Mr Teo Chin Hock, CSO tapped into the new commercial technologies to overcome many limitations of the 1st generation CCIS. Equipment procurement cycles were shortened and the latest hardware was fielded to provide higher technical performance. The use of COTS IT hardware also meant that the equipment was much less bulky resulting in a quicker deployment. It also enabled the rapid assimilation of NSmen during their annual in-camp trainings to learn the new CCIS and operate it more effectively. Recalling his experience with the new CCIS system when he was the Company Sergeant Major, 8 SAB Signal Company from 1999 to 2002, MWO Ng Hoe Lee said, *“Developed by DSTA with inputs from both the operational commanders and the Signal people, the 2nd generation CCIS was a marked improvement from its predecessor in terms of start-up time, ease of configuration, user friendliness and new capabilities such as planning modules.”*

The Chief of Army then, Major General (MG) Lim Chuan Poh said, *“The 2nd generation CCIS adopted a new paradigm in system development in response to the rapid advancements of COTS technologies. The design-field-design approach was adopted so as to provide the ability to test, validate, exercise with and field the system in stages and deliver the latest capability to the users at the earliest opportunity.”*



2nd Generation CCIS in the late 1990s

Ops users on the ground and the systems integrators from Signals had to constantly adapt, learn and make improvements to the system on-the-fly. It was a constant race against time to ensure that our technology remained up-to-date but the people triumphed against the odds, and the 2nd generation CCIS was operationalised. Spearheading this effort was then BG Desmond Kuek who was Commander 3rd Division, and it was his unwavering support that gave strength to the ground to push on despite seemingly insurmountable challenges



Operational planning using the 2nd Generation CCIS

Spurring Changes

During this period, recognising the need for more flexibility and responsiveness in the face of rapid technological changes, DSTA was established as a statutory board under MINDEF with defence technology organisations from the Defence Technology

Group and Defence Administration Group, under the leadership of Professor Su Guanng.

Likewise, the introduction of new software and hardware had also created a strong need for more system administrators to operate them in the Signal Formation. BG Desmond Kuek supported beefing up the nodes’ manpower with an officer-in-charge for each spilt node. Moreover, then Chief of Army, MG Lim Chuan Poh advocated a new COL establishment for the Signal Formation, which eventually became the COL establishment for the Signal Institute to undertake the important role of conducting training on C4 technology. As such, a review of the manpower structure and training was undertaken by then CO 3rd Signal Battalion, MAJ Chia Shee Wai. COL (NS) Low Jin Phang recalled that, as he saw through the whole implementation of the new structure to meet the new tasks, the COTS server experienced technical difficulties in supporting the increasing demands of the ops users.

The arrival of the high availability servers later provided more bandwidth and more software modules. The fully enclosed casing designed by DSTA also ensured that the servers would not be crippled by any dust trapped in the system. This was particularly important for overseas exercises in Australia to support the armoured brigades. In addition, to quicken the set-up time of the division HQ in the field, a new generation of expandable container command posts were trialled and fielded.

Towards the 3rd Generation Army and SAF (2000 Onwards)

The 1st generation SAF C4 was about building up our force readiness to meet Singapore’s basic defence. The 2nd generation SAF C4 was about evolving its capabilities systematically and as rapidly as possible to modernise our Army, Navy and Air Force. While this served well in making the Army a respected organisation, having painstakingly built up



Three-Ton Command Post in the 1990s

its systems and capabilities through judicious use of the resources made available by political commitment, the SAF's strategic environment had begun to change. New operational challenges, such as the need to counter transnational terrorism, and new resource challenges had emerged, and new opportunities arose through technological advancements. The Army pondered over the implications of these changes, whether it would remain relevant and successful through these changes, and whether a fundamental change was required for it to remain a successful organisation. This served to initiate the transformation journey towards a 3rd generation force.

The conceptual underpinning of the transformation was in Integrated Knowledge-based Command and Control (IKC2), conceptualised in 2004 in JCISD by then COL Ravinder Singh and the IKC2 Special Project Office, and then Director of Joint Ops Planning, BG Jimmy Khoo. IKC2 would enable the SAF to be a network-enabled, knowledge-based warfighting force, predicated on the Observe, Orient, Decide and Act (OODA) loop.

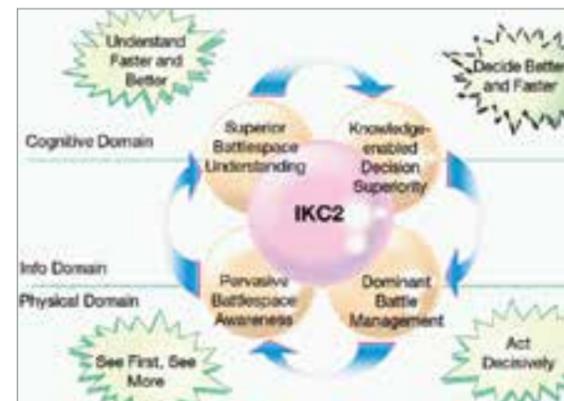
By exploiting C4 and information technologies (C4IT) and leveraging its tech-savvy people and systems approach to all aspects of its work, IKC2 enabled the SAF to operate with an accelerated OODA loop for decisive outcomes. IKC2 therefore served as a force multiplier that enabled the SAF to do more with less through the overlapping of sensors,

shooters and communication nets across the battlespace. Then Chief of Defence Force (CDF), LG Lim Chuan Poh, articulated to the SAF commanders that the possibilities with IKC2 were tremendous. It was a journey that would lead us towards a stronger SAF that would be able to deal effectively with threats across the entire spectrum of conflict. He also advocated investing more human resources in IKC2 and the Signal Formation.

IKC2 enabled the SAF to achieve greater force optimisation through the networking and sharing of tri-Service assets to better achieve mission and targeting requirements across the Service lines. Through the ability of the SAF to synchronise its actions, there was greater flexibility and efficiency of action. At the tactical level, this resulted in rapidly configurable, deployable and survivable, mobile and lethal forces that were able to operate autonomously within a netted environment across the spectrum of operations. In terms of decision-making, IKC2 enhanced the quality of decisions through new knowledge that was created through collaboration in the information domain. This reduced uncertainties in the battlefield and gave rise to better decisions. The speed of decision making also increased, enabling a higher tempo of operations.

Creating Capacity

To better support integrated operations planning for the SAF and to build up IKC2-enabled system capabilities, JCISD was significantly enhanced under the leadership of COL Ravinder Singh. Moreover, the Future Systems Directorate (FSD) was set up and led by then BG Jimmy Khoo, who played an instrumental role in the transformation effort. Together with the Services' C4, the networking requirements to enable information flow were streamlined across the Services. At the SAF level, a "top-down" strategy and governance to build interoperable communications and CCIS systems and a framework for integrating



IKC2 Framework (left) and members of the IKC2 Special Project Office (from left to right) then MAJ Andy Tay, CPT Melvyn Ong, LTC Ng Chee Meng and CPT Tan Ying Kiat. Member not pictured is then CPT Jacqueline Lee



a System-of-Systems was established. This was complemented with a "bottom-up" experimentation approach to enable the Services to conceptualise and experiment with new technologies and war-fighting concepts to realise IKC2. This was where defence engineers, commanders and C4 people came together to learn and deliberate with global thinkers such as Dr Gary Klein on "Recognition-prime Decision Making", and Dr Dave Snowden on "Sense-making in Complexities." These interactions between strategic thinking and engineering considerations were key to develop systems that were pragmatic and yet future proof.

Organisation Re-Structuring

IKC2 contributed to force transformation by enabling a more flexible and flatter C2 structure. Study teams from FSD and Services were formed to perform business process reviews to embrace IKC2. As a result, operationalising IKC2 was not just about the information communications system, but, more importantly, it transformed the command and control construct of the SAF to a task-organised command organisation. These were possible because of the maturing of IKC2 concept, the resolve of the Services and their commanders to fully exploit information communications technology, and the tremendous effort put in by defence engineers. For example, the RSAF undertook

a new, more flexible and capable structure to better handle the full spectrum of operations.

The new RSAF structure saw the amalgamation of six formations into five commands: the Air Defence and Operations Command, the Air Combat Command, the Participation Command, the Air Power Generation Command and the UAV Command. These five new commands enabled a greater level of integration with the Army, the RSN and Joint Staff. Similarly, the RSN moved towards the creation of Warfare Centres by integrating resources from various communities within the RSN. This enabled the RSN to achieve a knowledge-centric warfare approach to enhance the warfighting effectiveness of its platforms and combat systems. Similarly, the structures at the Joint Staff were reorganised to achieve a truly integrated and mission-oriented SAF. LG (NS) Neo Kian Hong, former CDF, recalled, "Information has truly flattened the SAF. The creation of C4I battalions and JTFs² changed the C3 systems through Command Post of the Future (CPoF). This was not a technology issue but a transformation of the command and control concept."

²Joint task forces, with units from across the three services of the SAF.



Container command post in the 2000s

Establishment of Enterprise Architecture by DSTA

A significant achievement by the defence engineers in DSTA was the establishment of IKC2 Technical Enterprise Architecture (EA). Its development was led by DSTA's then Deputy Chief Executives, Mr Sin Boon Wah and Mr Teo Chin Hock, and system architects Dr Yeoh Lean Weng, Mr Tan Yang How, Mr Pang Chung Kiang and a team of engineering architects. Enterprise architecture defined the interoperability standards across the MINDEF and SAF systems and its implementation was well executed. A central library of software modules at the SAF level was established which enabled software sharing at the SAF level, minimising duplication of programming effort and thus resulted in a 30% cost-reduction of the new CCIS development.



“Plug and play” characteristics of the Enterprise Architecture to enable different devices and applications to be connected.

The DSTA system architects also contributed significantly by sharing ideas such as the concept for robust and mobile ad hoc network, automated network management, multi-tier communications architecture, image compression, and information-on-demand. DSTA engineers introduced user-friendly man-machine interactions that helped to improve thinking processes of the commanders. Software features such as “drag and drop C2 system”, and a cognitive study on how to maximise the natural field of vision with horizontally-tiled displays optimised the integration of C4 systems into the command posts.

Recognising the growing threat of cyber-attacks, the 3rd generation CCIS was designed to be modular such that in the event that one component is compromised, the users could continue to operate the system and fight through the attack. The development of this new generation of CCIS was certainly in uncharted waters. LG (NS) Desmond Kuek, former CDF said, *“We find ourselves in a unique situation where there are not many others ahead of us to follow. The wisdom to forge ahead is something we will increasingly have to gain for ourselves.”*

3rd Generation CCIS

Achieving greater integration of C4 systems with intelligence systems was the next critical step in the evolution of IKC2. This effort was driven by then CDF, LG Neo Kian Hong. As the C4 people and intelligence people were both working on information management

systems such as information collection, fusion, analysis, content dissemination and database management, there was much ease in bringing the two communities together to build common skillsets and competency. This also allowed greater interactions between the defence technology, C4 and intelligence communities, resulting in more cross-sharing of engineering capabilities. Moreover, there was a greater need for process integration so that limited communications bandwidth could support the flow of large amounts of intelligence.

As such, the C4I Community was established to operationalise the information domain. LG (NS) Neo Kian Hong said, *“At the beginning, we only had the Army, while the other Services were branches. It was much later on that the other Services were developed for the three domains (Air, Land, and Sea). Now we have established a community for the fourth domain – the information domain. Although it is not referred to as a Service but a community, it has the same function: to raise, to train and to sustain a full capability and to open up new areas of development.”*

While we continue to learn from the advanced militaries, there were many uncertainties as the SAF was among the first movers in this area of transformation. The transformation was closely guided and supported by MINDEF leadership. An example of this was how Deputy Prime Minister (DPM) and former Minister for Defence, Mr Teo Chee Hean, and former Permanent Secretary for Defence Development, Dr Tan Kim Siew guided the SAF's cross-domain network development to enable new warfighting concepts.

Value in Peace

The benefit of operationalising IKC2 was obvious during the humanitarian assistance and disaster relief (HADR) operations to tsunami struck Indonesia Aceh. There was only a lean seven staff in the Network Management Centre. MAJ (NS) Yeo Siok Hock

commented that the operations had validated the training, and NSmen were ready to contribute with speed through skill. High bandwidth commercial satellite communications systems were deployed on board the Landing Ship Tanks (LST) and in different locations in Aceh. The system was the result of engineering efforts by DSTA and ST Engineering. The links enabled daily video conferencing between the Mission Commander, then BG Goh Kee Nguan and Task Force Commander, then BG Tan Chuan-Jin, and the SAF ops room back in Singapore. Additionally, communications were provided to non-governmental organisations (NGOs) deployed in Aceh.



Satellite antennae deployed to provide communications links between Singapore and Aceh

Besides HADR operations, IKC2 also played a critical role in the aftermath of the 9/11 terrorist attack on the New York World Trade Centre. The Army placed a renewed emphasis on local security operations to ensure the safety of Singaporeans and visitors in the country. The Signal Formation and DSTA put in place a robust C4 system, and links between police stations and army camps, to support protection of key installations such as the Changi Airport and Jurong Island.



Our soldiers patrolling Changi Airport



The SAF Centre for Military Experimentation

Army C4I Experiment Centre and Testing of IKC2

As part of the Signals initiative to transform the system development and technology testing process, the Army C4I Centre was established as part of the SAF Centre for Military Experimentation (SCME) under FSD, and coordinated closely with HQ Signals. Under the leadership of then Future System Architect BG Jimmy Khoo, and supported by defence engineers, a wide range of experiments were conducted such as collaborative command post, new wireless communications technology and man-machine interface to study the information communications technology's impact on force structure and design. FSD also helped to raise the level of IKC2 discussions in MINDEF and the SAF, to the point that IKC2 became a key topic in the Island Forum 2004, where strategic thinkers in the world were engaged in extensive dialogue on the topic with senior MINDEF and SAF leadership.

Then LTA Baey Chwee Leng Don, an NSF officer with SCME in 2005, recounted, *"I could not reconcile the thought of a soldier using his flashy PDA with the sweat, mud and rain that I frequently encountered during my field training in OCS. As a full-time national serviceman, I was privileged to participate in the various IKC2 projects and experiments, and explore COTS products together with DSTA engineers. Witnessing all the new systems being experimented before my eyes, I realised that I had been mistaken."*

The SCME approach enabled a more flexible and less manpower-intensive method of experimentation as compared to the traditional field trials. In Ex Wallaby 2003, the brigade CPoF experiment was conducted in Australia. A group of competent defence engineers joined the exercise to validate the technical aspects of the system performance. With IKC2, the experiment was designed to enable a brigade to dominate a larger battlespace with superior operational tempo and enhanced survivability.

The Experimental Brigade had successfully adopted a new C2 planning structure, which was found to enable increased situation awareness, improve collective knowledge-building and enhance decision making. After the exercise, Signal people came together with defence engineers to work on the issues encountered during the exercise and very soon started to prepare a new experiment in the subsequent year to explore the concept of distributed hubbing. It was clear that the evolution and experimentation of new IKC2 would never end. Today, the defence engineers and Signal people constantly assimilate the latest information communications technologies and find ways to exploit them in the operational environment.

In Ex Wallaby 2004, the Armoured Brigade HQ, led by then Brigade Commander LTC Benedict Lim, was decentralised to reduce the footprint of the command post so as to increase operations flexibility

and enhance survivability. By leveraging COTS 802.16 technology for the baseline communications infrastructure, coupled with video conferencing and collaborative planning software, the command post functioned just as effectively, despite the physically divided structure of the Brigade HQ. Defence engineers and Signal people systematically measured the effectiveness of the new wireless capabilities, and were able to quantify the benefits in an operational context.

DPM and then Minister for Defence, Mr Teo Chee Hean shared, *"You can see that the strength of the 3rd Generation SAF is not from superior platform numbers or specific platform capabilities alone. Rather, the strength of the 3rd Generation will be multiplied by the ability to network our various systems and capabilities together to achieve a quantum leap in total capability. For example, the way to counter combat tanks is no longer by fielding more and bigger tanks. These are necessary but this is not the only way to solve the problem. Our anti-tank capability will comprise a network of unmanned sensors, precision missiles delivered by Apache attack helicopters, smart bombs delivered by fighter aircraft, and armoured forces on the ground. The whole, as the saying goes, will be greater than the sum of the parts."*

The IKC2 Corridor

To string the whole range of experimentations, the IKC2 Corridor, a System-of-Systems approach to provide integrated development focus for C4 systems and quickly translate positive experimentation outcomes into operational capabilities was mooted. It enabled the implementation of a robust C4 system for peacetime operations in protecting key installations. Its centres of excellence brought operational users and defence engineers together to collaborate and transform war-fighting concepts and C2 doctrines.

Professor Lui Pao Chuen, then Chief Defence Scientist, played a pivotal role in guiding the Signal Formation and defence engineers

to conceptualise and implement new war fighting concepts and C2 doctrines. To support the 24/7 C4 operations demand, the 8th Signal Battalion was raised and subsequently evolved into the current day 10th C4I Battalion, which has integrated C4ISR capabilities for High Readiness operations. It also served as the knowledge proliferation engine for the SAF to enable continuous learning through experimentation and spiral development.



DPM and then Minister for Defence, Mr Teo Chee Hean trying our new IKC2 capabilities

The introduction of the spiral development approach to the manner C4 systems were developed was a significant shift from the earlier large-scale equipping of common communications system for the purposes of interoperability. Professor Lui had guided the Signal Formation to develop this strategy so that we could avoid block-obsolence and bring in the latest technologies for smaller scale pilot deployment for testing and experimentation. As a result, NSMen could adapt quickly to the latest technologies that were commonly used outside and they were familiar with.

Research and Development by DSO

As the C4 systems became increasingly integrated and new operational demands were constantly evolving, significant efforts in research and development (R&D) were also conducted by DSO. Mr Quek Gim Pew, Mr Wong Yue Kah and Dr How Khee Yin from DSO recalled that the partnership between HQ Signal and DSO had grown in breadth and depth, as the Signal people and commanders engaged in R&D initiatives and experimentation efforts to harness the latest networking, data communications, data fusion and artificial intelligence technologies. There were many challenges on the ground to get the right algorithms, and there were systems integration issues with COTS components. However, by working together with DSTA and Signals, the SAF and DTC successfully fielded many cutting-edge technologies, pushed ops-tech integration using advanced technologies and built indigenous R&D capabilities.



DSO engineers conducting project trial with Signal users

Battlefield Management System and Advanced Combat Man System

In addition to the CCIS that operated in command posts of divisions and brigades,

BMS and Advanced Combat Man System (ACMS) were also developed to allow soldiers and fighting platforms to receive orders from their HQ. It provided an electronic map and global positioning capabilities to show the locations of friendly and enemy forces. BMS and ACMS enabled soldiers to call on the capabilities of other fighting forces such as artillery and sensors to fight and see better. But this would not have been possible without the effort of C4 professionals and defence engineers that were proficient in the range of information communications technologies. Dr Ng Eng Hen, Minister for Defence, envisioned that in the near future, the increased network connectivity would allow individual soldiers to call upon an F-15, an F-16, or even navy ships to strike with pinpoint accuracy.



The Battlefield Management System

The genesis of BMS could be traced to a wired-up brigade experiment in 2000 by then Commander of 2nd Singapore Infantry Brigade, COL Ravinder Singh. The experiment was conducted focusing on two key tenets of terrain planning and tracking of ground forces digitally. Although the technology was not fully mature at that time, and many improvisations were made, the experiment demonstrated the prospect of information technology and mobile data networking in enhancing the Brigade's ability to plan and fight. In 2004, the Signal Formation started to work with DSO on developing a tactical information grid. In this project, besides Mr Wong Yue Kah and his DSO team, Mr Yao Shih Jih and Dr Henry Lee from ST Electronics



The Advanced Combat Man System

contributed in a big way to develop capabilities such as mobile ad hoc network and software features such as publish-and-subscribe that were useful to implement on-demand download based on geographical location.

These software features allowed the troops and ground commanders to determine what kind of information they needed and how the information should be presented to them. These changes sparked an innovative culture amongst the NSFs that participated and helped to create a positive perception of the usage of technology in the SAF. By participating in the development and thinking for themselves, they not only helped to revolutionise tactical capabilities, but also owned the solutions and enriched their NS experience.

Organising Knowledge - Integrating Administrative IT Systems with IKC2 Systems with Computer Security

Besides building up IKC2 capabilities for the SAF, efforts were also invested to create "organisational knowledge" in a bid to banish

silos in the knowledge realm. A knowledge management system was envisaged by then LG Neo Kian Hong that would not only act as a repository, but also a platform where knowledge could be synthesised through strong collaboration of our people across the SAF. Central to the creation of this organisational knowledge was knowledge communities such as the OCS (Officer Cadet School) Community of Practice led by then Commandant OCS, COL Png Bee Hin. To this end, formal knowledge communications were created based on physical organisations. These formal communities served as the main centre for knowledge sharing and synthesis. On the other hand, self-forming communities and virtual knowledge hubs were also formed based on common professional interests. These informal, unstructured communities served to enrich the knowledge landscape of the SAF.

To support these knowledge communities and virtual hubs, the SAF implemented enterprise System for Innovation, Learning and Knowledge (eSILK). It is a searchable online enterprise repository where legacy files are stored. eSILK also enabled some of the administrative processes such as the document registry and meeting processes to be reengineered and streamlined. This enabled a reduction in the number of registry personnel required, and improved decision making for meetings as the information



Community of Practice in the Enterprise System for Innovation, Learning & Knowledge

required was more readily accessible.

The next step in systems integration was to integrate the IKC2 systems with the logistics, manpower and training systems. Given that full integration would require substantial resources, and the amount of effort to sustain the integration across a wide range of systems was not sustainable, a decision was made to integrate those administrative systems that would contribute data to the IKC2 systems. This was the work done by the MINDEF Chief Information Officer (CIO) and SAF CIO, supported by defence engineers. This project brought IKC2 engineers together with engineers working on Administrative IT Enterprise Systems, led by Ms Pang Poh Cheng.

The integration across systems, especially integrating sensitive IKC2 systems with the less secure administrative systems, introduced computer security threats. The Security Division in DSTA was led by Mr Tan Ah Tuan, and the Division was enhanced to support the integration effort. A new computer and network security architecture was developed and overlaid on the enterprise architecture to provide the necessary connectivity and, at the same time, put security measures in place. As all the engineers were under DSTA, the integration went on efficiently. This was yet another benefit of including the former CSO and SCO under the integrated DSTA, and the SAF had benefited from it.

Close Ops-Tech Integration

Through the stories above, it was clear that at the heart of all the IKC2 developments was the close ops-tech partnership between MINDEF/SAF, C4 people, the DTC and Singapore Technologies. It was through this close partnership that ideas were able to be quickly translated to capabilities while meeting operational demands at the same time. This partnership did not happen by chance. It was through the visionary leadership of the late Dr Goh Keng Swee,

then Minister for Defence who sowed the seeds of our defence ecosystem.

This closed ops-tech relationship enabled setting of clear strategic directions for the capability development of the SAF, and identified the priority systems and technology areas to guide defence R&D. Mr Peter Ho, former Permanent Secretary (Defence), said, "*The exploitation of technology for strategic advantage was best achieved in an environment where experience was tapped, and knowledge was shared vertically and horizontally throughout the organisation.*"

The close ops-tech partnership also allowed relevant stakeholders from DSO and DSTA to sit in key MINDEF/SAF meetings and seminars to sharpen the SAF's ops-tech edge. This empowered MINDEF/SAF to conduct their own R&D to build up local defence technology capability in areas of strategic importance to Singapore, become a smart defence equipment buyer, and to work with local and international R&D partners to augment the SAF's technological capabilities.

Chapter Seven

DEFENCE CONSTRUCTION AND PASSIVE DEFENCE

Defence Construction

In July 1967, the first two SAF National Service battalions 3 and 4 SIR with 900 NSFs were raised. Some of the recent graduates from the first OCT course became platoon commanders or instructors in these battalions.

As it was not possible to complete the construction of two infantry battalion camps in time for the July 1967 intake, they were temporarily accommodated in four-storey Housing Development Board (HDB) flats which had been hastily converted into barracks at Taman Jurong.

Three camps were then under construction for 1, 3 and 4 SIR. These were at Guillemard Road and at the newly reclaimed land at Bedok. The camps were completed between 1968 and 1969, and the happy battalion commanders and their men moved into their new homes.



Guillemard Camp, circa 1969

There was no time to wait for the reclaimed land to settle before building Bedok Camp. The administration block of the camp soon started sinking, bit by bit. Due to safety concerns, the building was soon demolished!



Bedok Camp, circa 1976

The development of camps, operational facilities and training facilities kept pace with the accelerated rate of growth of the SAF ORBAT. Our engineers learnt from each project, to build facilities that were more efficient in the use of land and to meet users' requirements better.

The military camps handed over by the departing British forces were designed and built in the days when land was cheap and plentiful, thus the plot ratio (a measure of the ratio of built-up area to the land area) was extremely low. Many of these camps were used to house newly formed SAF units. Over time, this became impractical for land-scarce Singapore and many of these old British camps were torn down for re-development into modern camp complexes. These new complexes maximised the sharing of living space, with logistics, training and recreational facilities of units located within the same camp complex.

With the announcement of the withdrawal of UK troops, new plans were prepared for the build-up of the Air Force and Navy, to attain an initial operational capability by December 1971. These new units required barracks and offices, and logistics, operational and training facilities. It was not possible to build so many camps in three years, so camps like Seletar Air Base that the UK troops vacated provided housing for many of our newly formed units after some minor renovations and a fresh coat of paint.

In 1970, the UK had 36,685 troops in Singapore and employed many workers. They were occupying camps and facilities on 6,507ha of prime land, in 72 locations all over the island. Many of these facilities, like the Sembawang Naval Base and the Pasir Panjang Army Complex, had higher economic value to the country than military value to the SAF. Therefore, there was a need to convert these facilities for economic use and to redeploy the workers made redundant by the UK's withdrawal.

The Bases Economic Conversion Department (BECD) was set up in February 1968 to perform this vital transitional task, with Permanent Secretary (Finance) Mr Hon Sui Sen in charge. Then Prime Minister (PM) Lee Kuan Yew stated in his memoirs that he had placed BECD under the PM's Office to give Mr Hon Sui Sen more clout when dealing with other ministries.

Sembawang Naval Base was converted into a commercial company, Sembawang Shipyard, with the assistance of British company, Swan & Hunter, while Sembawang Wharves and some warehouses were retained by the SAF for visiting naval ships.

The weapons and electronics workshop of the naval base was spun off as Singapore Electronics and Engineering Limited (SEEL), the forerunner of today's Singapore Technologies Electronics.

The airfield at Seletar Air Base was used for general aviation and the base was partitioned into two parts, East Camp for military use and West Camp for commercial use. Tengah Air Base became the first fighter airbase of the RSAF and parts of Changi Air Base were redeveloped into Changi Airport, after MINDEF agreed to exchange it for Paya Lebar Airport which was to be developed for the RSAF's use.

Blakang Mati, now called Sentosa, was

developed as a tourist resort island. Part of the large Pasir Panjang Army Complex was developed into the NUS, Singapore Polytechnic, Institute of Technical Education and for light industrial use. The Normanton Oil Depot was developed into a condominium. Some of the Royal Electrical and Mechanical Engineers workshops at Ayer Rajah Road became Singapore Automotive Engineering (now part of ST Kinetics). The remaining workshops were then taken over by our Army.

Then Senior Minister Lee Kuan Yew summed up the base conversion exercise in his book 'From Third World to First' as follows, "The withdrawal was carried out with goodwill on both sides. The 30,000 retrenched workers were absorbed by industries we attracted from abroad. When the withdrawal was completed in 1971 our people were quietly confident. There was no unemployment, and no land or building was left idle or derelict".

Just as important for us was the build-up of the SAF to take over the responsibility for the defence of our own country.

Masterplanning for Defence Construction

Masterplanning for defence construction to support the growing SAF ORBAT began in the early 1970s, soon after the completion of the complex base conversion exercise. The biggest challenge for us, however, was not in the development of camps but in optimising the use of land in Singapore. Our need for army training land was more than all the lands occupied by the British forces. In fact, training land for the Army accounted for about two-thirds of the land allocated to MINDEF.

Airfields were the second largest user of land, followed by ammunition depots. Not only did airfields require large areas, some 700ha each, they also imposed height constraints on developments surrounding them. The land

occupied by ammunition depots were not as large as compared to our airfields, about 100ha for a depot, but the amount of land that needed to be sterilised from development to create a safety buffer was about 300ha. The development of an ammunition depot therefore required a total of about 400ha of land.

Our air defence weapons needed to be deployed on hills but these were rapidly being cut down for reclamation of land for industrial use in Jurong. The remaining hills had to be preserved and this was done after the Singapore Cabinet approved of the need. With this decision to save our hills, land reclamation had to depend on imported sand.

The integrated SAF command, control, communications and intelligence system required many sites for sensors, communication systems and operation centres. The land use masterplan of MINDEF therefore needed to balance all demands of the SAF and to optimise the use of land at the global level.

Camps occupying prime land were returned to the state in exchange for less valuable land in rural areas. An example in point was the exchange of Tanglin Camp for the farm land at Bukit Gombak to build the MINDEF Complex.



MINDEF Complex

Masterplanning the use of our lands and facilities has continued over the years as a major area of focus by our planning staff. To better utilise land resources, it was important to intensify land use by grouping different units at the same location as and when feasible to form camp complexes. The first of such camp complexes was the Ayer Rajah Camp

completed in 1986. Such complexes allowed the pooling of common facilities and resources more effectively so as to free up more land and resources for other purposes.



SAFTI Military Institute (top) and Pulau Tekong (bottom) - Inspiring a New Generation of Soldiers

In the 1990s, MINDEF and the SAF focused on inspiring a new generation of soldiers with the development of SAFTI Military Institute, the Basic Military Training Centre at Pulau Tekong to train our NSFs and the Singapore Discovery Centre to enable our younger generation to better appreciate how Singapore has developed to become the nation it is today.

The Army Museum was built close to the Singapore Discovery Centre, as a facility to preserve the heritage of the Singapore Army, as well as honour the contributions and celebrate the experiences of our soldiers.

The evolution of our armed forces into the third generation SAF required custom solutions for specialised needs. Our architects and engineers adopted a design thinking

approach to develop facilities that were functional, prudent and user-centred. This entailed considerations on the broad spectrum of user behaviours and expectations, which would consequently determine how they will experience the built environment. An example was the Multi-Mission Range Complex which was developed to ensure that servicemen have a one-stop centre for all-weather arms training in an urban environment.



Army Museum

In planning and designing building and infrastructure development, the utilisation of Singapore's scarce land, energy and water resources must be optimised. Design and construction needed to be sustainable, and features like renewable energy, water conservation and recycling, and rain water usage were incorporated wherever feasible.

Our building and infrastructure design was based on the four tenets of operations, security, user experience and sustainability.



Multi-Mission Range Complex

Masterplanning our Air Bases

During the development of the OMP of our air bases, we found that the amount of land used by the UK RAF for Tengah Air Base was about half of that needed for a modern fighter air base. The reason was that Tengah Air Base was designed by the RAF for the operation of fighter aircraft lined up in a straight row to maximise maintenance efficiency. The war in Vietnam and the Six Day War in the Middle East had shown the vulnerability of fighter aircraft to artillery bombardment and air strikes. That being said, the survivability of our fighter force could be improved through dispersed ground operations. To implement the dispersed aircraft concept of operations, our Air Force would need to double the land area of Tengah Air Base. This was done by closing down the nine-hole golf course of the air base. Many trees were also planted to provide cover for our aircraft from observation.

We were paranoid about the closure of our runway system for operations. Should this happen when most of our fighter aircraft were on the ground, they could not takeoff until a runway strip could be cleared. We could lose precious hours of fighter operations which could be critical for our nation. On the other hand if most of our fighter aircraft were airborne and our runway system was closed for a few hours we could lose the fighter force when they ran out of fuel. Hence, we created a runway system that could not be closed, using long runways and multiple taxiways in each airfield and multiple airfields in Singapore that could support fighter aircraft operations. All our expressways were studied and suitable stretches were developed as emergency runways. An island, Pulau Sudong south of the Singapore island was found suitable for use as an emergency airfield. An emergency runway was built there.

The development of our first airbase for fighter operations began in 1971 when the RAF handed over Changi Air Base to the

Air Force to house the A-4S Skyhawk fighter aircraft that we had bought from the US Navy and refurbished and upgraded. The first few aircraft were completely rebuilt by Lockheed in their California plant in the US, while the rest were built in Singapore by Lockheed Aircraft Services Singapore (LASS). Mr Chinniah Manohara, a young mechanical engineer from SMG, was the project director with the responsibility for planning, design and construction of the air base.



Lim Chu Kang Road Emergency Runway

Operational facilities like squadron headquarters and operations post and aircraft parking sheds were completed and the A-4S Skyhawks started operating from Changi Air Base. Meanwhile, MINDEF agreed with the Ministry of Communications (MINCOMM) to exchange Changi Air Base for Paya Lebar Airport in 1975. This decision resulted in the abortion of all air base construction projects under development in Changi Air Base. As Paya Lebar Airport would still be in full operation until all commercial flights were successfully moved to the new Changi Airport in 1980, the RSAF could not construct any operational facilities in Paya Lebar. In the meantime, the RSAF would have to operate their Skyhawks in Changi while the airport was being constructed. The mutual interference between the airport construction and fighter aircraft operations from the same airfield grew with time; eventually, the RSAF made the decision to move the Skyhawk squadrons to Tengah Air Base.



Changi Air Base, circa 1954

The effectiveness of our fighter aircraft is a function of the number of missions it can perform each day. The number of missions would depend on the availability of pilots and the speed at which the engineers and logistics staff can refuel, repair and rearm the fighter aircraft. The most efficient way to refuel a fighter aircraft would be to have fuel on tap. The speed of repair would depend on the experience and skill of the engineers and technical workforce, and the availability of spare parts. The storage, supply and loading of armament is a critical function. The challenge working with armament is safety. If a fighter aircraft can carry 7 tons of armament and it flew five sorties, 35 tons of armament would have to be transported from the armament depot in the base to the hangar to rearm one fighter.

The large quantity of bombs and weapons that modern fighter aircraft can carry makes storage and transportation of ammunition in an Air Base a very complex problem. The safety distance required for different elements of an armament system is a major design driver of an Air Base.

The project team for the development of RSAF air bases required engineers from many

disciplines. PWD Airport Branch was leading the development of Changi Airport and had built up a strong team for the planning and design of airport infrastructure systems. PWD responded to the request by MINDEF to lead in the planning and development of Tengah Air Base by assigning their most promising engineer, Mr Liew Mun Leong to lead the PWD team that was named Air Base Redevelopment Team (ART). The operational expertise was provided by the RSAF with COL Gary Yeo as the leader of the operations team. The operations team used the experience gained by the Israelis in developing their own air bases to develop the OMP for Tengah Air Base.

The Engineering team, led by one of the promising air engineering officer of the RSAF, MAJ Tay Kok Khiang, developed the Engineering Master Plan (EMP) which was a translation of the OMP into an engineering plan, taking into consideration engineering practices and constraints. ART then used the EMP to guide the planning of the taxiway system to connect the hangars to the runway.

As a fighter aircraft was most vulnerable when taxiing, the time taken for taxiing and waiting for take-off was designed to be as short as possible. A second taxiway was built to contribute to the reduction of exposure time. Hangars were also used to reduce the vulnerability of the fighter aircraft during refuelling and rearming for the next sortie. The nine-hole golf course around the Tengah Officers Mess was redeveloped to house a fighter squadron. Arrangement was made with Raffles Country Club for the staff of Tengah Air Base to play golf there.

Besides protecting the fighter aircraft, the project team identified all the operational systems that would be needed to support operations despite enemy actions. An example was the electricity generation and distribution system. As electricity was needed for almost every air base operations, a very resilient electricity generation and distribution system,

with multiple levels of redundancy down to generators for individual fighter aircraft, was implemented.

A rapid runway repair capability was built up to repair the part of runways that could be made unusable by enemy attacks.

Plans for Paya Lebar Air Base were made at the same time as that for Tengah Air Base by the same team. To accelerate the conversion of Paya Lebar Airport for military use, MINCOMM accepted the request from MINDEF for the construction of a parallel taxiway east of the runway while it was still being use as a civilian airport. PWD Airport Branch was very helpful in the planning, design and construction of this taxiway and others in the land east of the runway.

After Changi Airport was officially declared open on 29th December 1981, the RSAF was able to move into Paya Lebar and begin the construction of operational facilities located in the east of the runway. The hangars and airport facilities once used by commercial flights were converted for military aviation use. Singapore Aerospace took over the SIA hangars in Apron C.

There was a concern that MINDEF could not use all the space in the passenger terminals. Air Logistics Department and SPO managed to make maximum use of the space in Terminal A while HQ Singapore Air Defence Artillery (SADA), the School of SADA and Central Missile Support Base occupied Terminal C.

Within a decade, the RSAF was operating their fighter force from Tengah Air Base and Paya Lebar Air Base to achieve their concept of operations of providing maximum protection and minimum turnaround time, to maximise the fighting potential of our fighter force.

Dispersed fighter operations made the fuel storage and distribution system through a network of pipes a major challenge for our

mechanical engineers. So did the electrical supply and distribution system which had to continue functioning in the event of battle damages. Furthermore, the extensive use of fibre optic cables for many systems and facilities, and networking them securely together also posed engineering challenges.

We projected future threats to our air bases like chemical and biological agents and precision guided weapons with sizable warheads. The protective system of our air bases took such future threats into consideration in their design.

Over the years, with the development of four air bases, our engineers had the opportunity to continuously learn and improve to be better designers and project managers.

Masterplanning our Naval Bases

In the early 1970s, the Navy needed a naval base for their missile gun boats (MGB), patrol craft and LST. Pulau Brani, located in the Keppel Harbour, was found to be the ideal site in 1971. It was a naturally sheltered island, with an area of 122ha. A British consulting company, Sir Bruce White, Wolfe Barry and Partners was commissioned to plan, design and supervise the construction of the Pulau Brani Naval Base.

It was completed at the end of 1973 and was declared open by then PM Mr Lee Kuan Yew on 26th January 1974. Through this project, the young engineers learnt the business of planning and designing a naval base.

Soon, a second naval base was required to accommodate the growing ORBAT of the RSN. Tuas, at the western tip of the island, was an ideal site. At that time, our engineers had just completed Phase 1 of the development of Tengah Air Base and Paya Lebar Air Base and were eager to transfer their experience in masterplanning, design and project management to this new project. Specialist consultants from

overseas were also engaged to assist in the development of the OMP.



Opening of Pulau Brani Naval Base by then PM Mr Lee Kuan Yew on 26th January 1974 (Photos credit: Ministry of Information and the Arts Collection, courtesy of National Archives of Singapore)

The key of the naval base was quick turnaround time for refuelling and rearming, maximum wharfage, and storage of ready-to-use missiles and ammunition in a site which was not large enough for the standard safety distances to be applied. It also had to accommodate the commercialisation of storage and maintenance facilities. The subsequent EMP was formulated by our engineers.

Local consultants were engaged on the design of large-scale maritime structures, and also undertook the detailed design of some of the conventional facilities.

Tuas Naval Base was officially opened by then PM, Mr Goh Chok Tong in September 1994. Speaking to the Navy servicemen and women gathered at the function, he said, “It is the people, who will make the Tuas Naval Base outstanding and the RSN’s fleet fighting fit. It is your foresight, heart and spirit that will decide the reputation of the Tuas Naval Base.”

Meanwhile, Brani Naval Base was found to be incompatible with the revised national land use masterplan as the site would be needed for the future expansion of the Port of Singapore Authority’s (PSA) shipping container terminal. The construction of the causeway connecting Sentosa to the mainland and the busy traffic in the Keppel Harbour were additional push factors for the Navy to look for a replacement site for Brani Naval Base.

The conceptualisation of the Changi Naval Base started in 1990. The location of the base would be in a patch of the sea off Changi that would not be affected by the height constraints of Changi Airport. The site was chosen to be between the planned third and fourth runways. Land reclamation would be needed, and the area had to be large enough to accommodate more and bigger warships, logistics, recreational and sporting facilities.

The long lead-time item for the development of Changi Naval Base was land reclamation

and so it had to proceed as quickly as possible in order that the base could be completed by 2000, to make way for PSA container terminal development. Land reclamation work commenced in 1992, just two years after the base was conceptualised. With the experience gained from the Tuas Naval Base development, the OMP and EMP were formulated in-house using integrated project design teams comprising operations staff, engineers from DSTA, local consultants and experts from our local universities. The main challenge was in providing dynamic engineering solutions that were able to meet the operational requirements of the RSN in an optimal and cost-effective manner.

Changi Naval Base was completed a few months behind schedule as the project was more complex than anticipated, with changes in operational and technical requirements during the course of the project. The ceremony to mark the berthing of the first deep draft vessel, the USN carrier, USS Kitty Hawk at Changi Naval Base on 23rd March 2001 was a major milestone for the completion of seaward facilities of the base.

Our Ammunition Storage Challenges

Storing ammunition safely was one of the challenges that the SAF faced. Large amounts of valuable land around each of our ammunition storage facilities had to be sterilised for explosives safety reasons. With Singapore’s land scarcity, there was a push to free up this land for other developments. We needed to

level up quickly on new technologies that could reduce hazards arising from accidental explosions in ammunition storage facilities.

We began the planning and design of the SAF stockpile as a large-scale system in the 1970s. The ammunition stockpile system would include production, storage, distribution and maintenance.

A major component of the ammunition stockpile system was the ammunition store houses. We discovered that the basic load of ammunition of our Army units included high explosive items which were kept in their unit magazines. The safety distance required for the storage of these high explosives items extended in many cases outside the fence line of our camps. Compliance with our explosive safety regulations would require the high explosive items to be removed from our unit magazines. But the units needed these high explosive items to be operationally ready. The conflicting needs of operational readiness and public safety were finally resolved by developing ammunition store houses for the basic loads of battalions in the ammunition depot located closest to their camp.

However, the main issue – to determine the optimal number of ammunition depots that we could locate in Singapore, at a minimal cost to the nation while meeting the storage, readiness and survivability requirements of the SAF, remained. Each depot would require an area of about 100ha for the construction of the storage facility, and an area of 300ha to be sterilised as safety buffer.

The main ammunition depot of the Army was in the nature reserve. As the surrounding land had been protected by the Nature Reserve Board from development, there was no cost to the land sterilised by the explosives safety buffer. The Navy required some of their missiles and ammunition to be stored in their naval bases for operational readiness. No land was available for safety buffer as prescribed

by available explosive storage standards. Specially designed and constructed magazines had to be built for our naval bases.

It was a constant challenge to find and develop new technologies for the storage of ammunition that would reduce the amount of land that would be sterilised. Urban Redevelopment Authority’s (URA) plan to redevelop Seletar Air Base in 1994 for the Seletar Aerospace Park compelled us to take the next significant step in the development of ammunition depot through the use of rock caverns. This alternative was first studied in the 1970s during the system study of our ammunition stockpile storage system but was rejected due to the high cost of construction.

The explosives safety standards of the UK that we had adopted were very conservative with regard to underground storage. The amount of land that would be sterilised would remain the same as that for above ground storage. As the construction cost of underground ammunition facility would be considerably higher, there was no economic case for an underground ammunition storage facility, despite our intuition telling us that there was.

Learning About Explosives Safety from Overseas Experts

We had been attending seminars on explosives safety since the 1980s to learn from experts in the field and to get to know them. One of the best known seminars was the biennial Department of Defense (DoD) Explosives Safety Seminar, where the world’s experts gathered. We became friends with some of the experts and were invited to visit their laboratories and tests.

In one DoD Explosives Safety Seminar, the US Defense Nuclear Agency (which evolved into the Defense Threat Reduction Agency (DTRA)) presented a paper on Distant Runner, a test for the US Air Force on the effects of bombs stored inside a third generation concrete



Changi Naval Base Berthing Facilities

aircraft shelter. The test would be done at the White Sands Missile Range, New Mexico.

We received an invitation and a team of eight engineers were sent to attend the test.

The tests showed that the explosion of 48 units of 500-pound MK 82 bombs each with 87kg of Tritonal explosives would destroy the aircraft shelter and everything inside except the underground chamber that was designed for storage of nuclear weapon bombs. The overpressure generated and debris throw distances were as predicted by the calculations.



Team of engineers (fourth from the left) and ammunition specialists (fourth from the right) studying the effects of explosion on aircraft shelters at Distance Runner tests at White Sands Missile Range on 18th November 1981

Distant Runner marked the first explosives safety test attended by engineers and ammunition experts from Singapore.

The US Navy had a small group of experts located at the US Naval Facilities Engineering Services Centre (NFESC) responsible for specifying safety distances for all US Navy shore-based ammunition facilities and determining their designs. This group had been active in the development of explosives storage technology and their results were frequently presented at the Explosives Safety Seminars. One of the leading experts of NFESC was Mr Bill Keenan. We met at the Distant Runner Tests and later became good friends.



Explosion with 4176kg of Tritonal destroyed the shelter completely as the door of the shelter had prevented venting of the blast

International Collaborations in Explosives Storage Safety

Following our meeting at White Sands Missile Range, Mr Bill Keenan had progressed up the ranks in NFESC and was appointed the Head of the Explosives Safety Group. In 1994, he came to Singapore with a proposal for collaboration in the research and development of the use of water to mitigate the effects of blasts. He told us that laboratory tests done by NFESC had shown that a reduction of the peak pressure by 80% to 90% was achievable. They had not yet performed simulation studies with high performance computers or gone beyond laboratory-scale testing. The proposal was exciting as the search for ways to minimise the use of land for explosives safety had been one of our major preoccupations since the 1970s. Besides the need for land for safety around our ammunition depots, we also needed to find a solution for the storage of 155mm shells in the field for our Army.

Mr Bill Keenan also proposed to collaborate on a project that NFESC had gone into full-scale

development and certification. This project was the use of low density concrete walls or non-propagation walls to prevent sympathetic explosion of explosives stored in different chambers in an explosives storehouse. This technology was one of the pillars of the High Performance Magazine that they had been developing to minimise the land needed for safety around magazines in US naval bases. We told Mr Bill Keenan that his two proposals were of great value to us and that we would visit NFESC to follow up. We sent a request to our Defence Attache in Washington then COL Lee Sing Kong to seek support from the technical agencies at the Department of Defense and Department of Navy for Singapore to collaborate with NFESC on the two projects.

In August 1994, COL Lui Pao Chuen led a team comprising Mr Lim Chee Hiong and Mr Ong Yew Hing to Port Hueneme, the largest US Navy port in the West Coast, where NFESC was located. The purpose of their visit was to draft a Memorandum of Understanding for collaboration in research and development on these two projects.

We were surprised not to find Mr Bill Keenan when we arrived to the meeting at NFESC. We were told that Mr Bill Keenan had just retired and had moved his home away from Port Hueneme. His successor, Mr Jim Tancreto, co-hosted the visit with the Head of the Water Front Structures Division, Mr Robert Odello. All the NFESC experts appeared at the welcome session. US Navy Lieutenant Linda Lancaster told us that she represented the Department of Navy to facilitate the paperwork that would be needed for information exchange. When we asked how long the paperwork would take, she replied that it was typically a two-year process for staffing. She advised us that we would need a champion to navigate through the bureaucracy of the Department of Navy. Our champion would have to go from office to office to garner support so that approval could

be obtained sooner than two years. As we had expected this we had made arrangements to call on the officers in the Department of Navy, identified by Defence Attache then COL Lee Sing Kong, after our visit to NFESC.

We briefed the meeting that the shortage of land in Singapore had motivated us to develop an ammunition facility that would be excavated in rocks. This facility would help us achieve our goal of reducing 90% of the amount of land needed to be sterilised by the storage of ammunition in conventional bunkers built on the surface.

Water mitigation and non-propagation walls could thus be keys to the achievement of this goal. As the phenomenon of ground shock of an explosion, and its effect on modern apartment buildings of reinforced concrete were not well studied, we sought their advice on their approach to such research.

Mr Robert Odello shared he had done a literature survey some years ago on all the work that had been done in the US on the storage of ammunition in stores that were built underground. He showed us a copy of his report which he had brought with him. COL Lui Pao Chuen promptly asked for the release of this report which Mr Robert Odello could not accede to without authorisation from the Department of the Navy.

We requested for him to lend us the report for a night for bedtime reading in the hotel room. He agreed and we spent the night reading the interesting report. The part that intrigued us was that there were two formulae to calculate ground shock safety distances that had found their way into the DoD Explosives Safety Standards. Using one formula would yield a required safety distance of 60m which would be really great for us but using the other would yield a required safety distance of 300m which was bad news. We asked Mr Robert Odello the following morning whether he had found an explanation for this

discrepancy. He replied that he could not and speculated that there could be a typo error in the formulae.

COL Lui Pao Chuen led a team to visit the DoD Explosives Safety Board in Washington in 1995 to brief them on our Underground Ammunition Facility project, and to be an observer at the meeting in which the results from the Joint US-ROK Technology Development programme were deliberated. We were the first foreigners to be allowed into such meetings. When COL Lui Pao Chuen broached the subject of the two formulae for ground shock to Dr Chester E. Canada, a member of the Board, he told us that there was nothing that the Explosives Safety Board could do about the uncertainties in the formulae. We could not get any resolution from the Board and would have to decide which one to use. This cemented our resolve to do our own research on ground shock. The meeting also opened the door to our add-on tests to US-ROK tests at Magdalena, and these add-on tests were known as the 1996 Singapore Ground Shock Tests.



Ground Shock Tests in Magdalena, New Mexico, USA, 1996

Passive Defence

Passive defence covers measures in building or infrastructure design and construction taken to resist in-place and minimise damages caused by hostile actions such as bombing. The critical need of Singapore for passive defences was self-evident. The high value of land in our small country gave us additional

motivation to explore new technologies and solutions that could meet our unique needs.

Building Our Local Capabilities in Passive Defence

Passive defence complements the active defence provided by the SAF. It has been an important component of Singapore's defence and has seen steady growth over the last 40 years.

We had therefore been working steadily since the 1970s to build up our technology in passive defence and protection. In the early 1980s, we were smart buyers and users of foreign technologies. We engaged specialist consultants from different countries and tapped on their experiences and knowhow to help us develop our operations facilities. In the mid 1980s, we started collaborations with our local universities and began to carry out in-house design of protective facilities using existing design codes. We needed to build up our indigenous protective building and infrastructure engineering capabilities to enhance the survivability of personnel, assets and critical operational functions. In 1989, Mr Ong Yew Hing was sent to the Royal Military College of Science (RMCS) in the UK to study for his Masters of Science in Weapons Effects on Structures under the Defence Technology Training Award. MINDEF had been sending engineers to the RMCS for other courses before and this was a new course that had just started in 1987. Another seven engineers were sent by MINDEF for the course until it was discontinued.

The RMCS campus at Shrivenham had a small explosives test range where up to 430g of TNT or its equivalent could be tested. As part of the course, students were required to do a project involving either explosive tests or numerical modelling using computational fluid dynamics. During his studies in RMCS, besides acquiring the theoretical knowledge and learning how to design protective

structures, Mr Ong Yew Hing also learned that the ability to carry out explosive tests and numerical modelling were two critical factors in the build-up of protective engineering capabilities. They were essential enablers for new protective concepts and designs to be studied and validated.

In our effort to build up our in-country capabilities in protective engineering for the development of the UAF, we were on the lookout for people with the right skill sets. We came across Dr Karen Chong, a PhD in nuclear engineering who was finishing a research project at NUS in blast modelling and offered her a job in LEO (Lands and Estates Organisation, which later became part of DSTA). She eventually became our expert in modelling and simulation, and explosive testing. We also hired Dr Zhou Yingxin, a mining engineer who built up our capability in rock engineering for the UAF project. Dr Zhou and Dr Chong were the first two PhDs employed by LEO. Both had pursued their PhDs in fields of their respective interest but could not find jobs in Singapore that required their expertise acquired through years of PhD studies and research. The UAF project and the associated technology development that LEO ventured into provided the opportunity



Our first engineer at the Royal Military College of Science, Weapons Effect, Mr Ong Yew Hing, on Structures Masters Programme in the UK 1989

for them to grow and excel in their respective areas, while contributing to the build-up of in-country capability to enhance defence building and infrastructure.

In the early 1990s, we set up a long-term technology development programme to develop in-country capability in protective technology. Protective technology is a niche area that entails understanding the effects of weapons on buildings and infrastructure, and then developing protection systems against such effects. We knew that there was a need for fundamental research to close technology gaps in protective technology. In his speech in 1997, then second Minister for Defence, RADM (NS) Teo Chee Hean said, "LEO needs to collaborate with overseas institutions, as well as leverage the research and development potential of NUS and NTU to develop indigenous know-how and technology which best suits our needs and circumstances." The Centre for Protective Technology was set up at NUS and the Protective Technology Research Centre was set up at NTU a year later. The two centres were set up to spearhead research efforts to provide scientific and engineering solutions to meet the national need in weapons and defence systems, and address emerging national protective technology challenges for the government and industry. We also leveraged expertise in our research institutes, such as the Agency for Science, Technology and Research's (A*STAR) Institute of High Performance Computing and DSO, for integrated efforts to fill protective technology gaps.

We had many projects that would help to build up our engineering capability, and needed a long term view of capability building. Instead of taking the easy way out of employing consultants to get the project done, we continued to pursue opportunities to train our engineers in the specialised area of protective technology to undertake these projects. Today, we send our engineers to



Explosive Testing at Pulau Senang in 1998

train under renowned experts in the US¹, the Netherlands², Norway³, Switzerland⁴, Canada⁵ and the UK⁶. When our engineers come back, we will provide them with exciting project opportunities such as the development of new explosive storage concepts and facilities and new bases, to hone their engineering capabilities.

Local Large-Scale Explosive Testing

There was a critical need to validate our protective design against actual explosions. We needed to build up the confidence and capability to do the tests ourselves. On his return from the MSc course in RMCS, Mr Ong Yew Hing and a group of engineers began planning to carry out explosive tests in Singapore. The first test was conducted in 1990 at the Sungei Gedong live firing area to investigate the effects of contact explosions on reinforced concrete slabs. The test was carried out using 81mm mortar as this was the largest ordnance allowed to be detonated at the range.

We had to look for alternative sites to test ordnances with larger explosive payloads. We performed our next explosive tests in 1992 in Pulau Senang, an island south of the Singapore island. The tests were to study the effects of 155mm artillery rounds on concrete slabs. The Sungei Gedong tests and Pulau Senang tests were the predecessors of

our large-scale explosive test programmes on structural components that have continued up till today. Data from such large-scale tests are difficult to come by as they are usually classified. The tests give us the confidence that our protective designs will withstand the threats concerned.

There was still a limit to the amount of explosives we could detonate on Pulau Senang. For safety reasons, we could only test single rounds of cased charge on the island. To study the effects of accidental explosion in ammunition storage, we needed access to larger test sites that could detonate up to tens of tons of explosives, which could only be found overseas. Our international collaborations allowed us to participate in joint large-scale explosive testing programmes. As large-scale explosive tests are very costly, such collaboration allows countries to share costs as well as test results and findings. Since 2000, we have participated in overseas large-scale explosive tests in Australia, Sweden and the US. Some of the test sites in these countries are a few times the size of Singapore.

Sharing our Knowledge with Other Government Agencies

The knowledge and experience gained by our engineers in armaments, and building and infrastructure, were shared with other government agencies through collaboration in various projects, and in the Explosive Safety Committee, that was co-chaired by the Deputy Commissioner of Police and Chief Defence Scientist. The committee was set up by the MHA and MINDEF to provide the Singapore Government with professional advice on safety matters in the

handling, transportation, storage and usage of explosives.

Following 9/11, the coverage of the committee was extended to include fire and chemicals hazards and the committee was renamed as Explosive, Fire and Chemical Safety Committee (EFCSC). One of the hazards identified then was the transportation of chemicals by tanker trucks from the container port terminals in the city to Jurong Island. Though the transportation would meet international transportation requirements for hazardous chemicals, the requirements did not consider an attack by terrorists. The committee considered that any leakage of hazardous chemical when the tanker trucks passed through populated areas was not acceptable and recommended that the tanker trucks be transported by sea in a barge to Jurong Island instead. The company involved was not pleased with this recommendation but complied as it respected the recommendation from the committee.

Civil Defence Shelters

In the early 1970s, preparation for the nation to operate during wartime conditions was identified as an important task that planners in MINDEF should address. MINDEF engaged an expert from the UK Ministry of Defence to learn from them their experience in preparing the nation to operate in wartime. One of the subjects was the protection of civilians from the effects of weapons. In fact, the London subway had served as bomb shelters for many Londoners.

In a period of tension, our NSmen will be mobilised for operations, which means that their families will not have them at home to lead and provide comfort. The safety of their family members is of paramount importance to our NSmen, and thus, the protection of our civilian population from weapon threats in civil defence (CD) shelters is very important. CD shelters would also provide reassurance

to our troops that their family members at home would be protected.

Following the government's decision to proceed with the construction of the Mass Rapid Transit (MRT) in 1982, then Minister for Defence, Mr Goh Chok Tong tasked the SPO to study the use of the MRT system as bomb shelters, as was done in London during World War II.

The study concluded that our MRT underground stations could be used for civil defence but the tunnels would not be suitable as the temperature and humidity would be too high for comfort. The MRT system would be underground in the city area with 15 underground stations, while the rest would be on elevated tracks. The 15 underground stations could be developed for use as large CD shelters to be operated during air raids. The roof and walls of the underground MRT station would, however, need to be reinforced to resist the effects of a direct hit of an aerial bomb.

MINDEF argued that the case to harden underground MRT stations was compelling. In the event of an air raid, people would run into these stations believing that it would be safer than being above ground. If a bomb should hit an MRT station and penetrate the roof or wall and explode within, the number of casualties would be large.

The Singapore Government eventually decided that 9 out of the 15 MRT stations (Braddell, Newton, Somerset, Raffles Place, City Hall, Marina Bay, Lavender, Bugis and Tiong Bahru) would proceed to be developed for use as CD shelters.

As the nine CD shelters in MRT stations could only accommodate about 100,000 people, there was a need to build shelters in HDB new towns to provide as many shelters as possible in the shortest time. MHA developed a comprehensive plan to protect the entire

¹ University of Florida, Center for Infrastructure Protection and Physical Security, Colorado School of Mines

² Delft University of Technology

³ Norwegian University of Science and Technology

⁴ EPFL Ecole Polytechnique Federale de Lausanne, Switzerland

⁵ University of Toronto, Canada

⁶ Imperial College and Leeds University in the UK

civilian population. The plan was approved by the Singapore Government in September 1986, and shortly after the National Shelter Bureau (later renamed as the Civil Defence Shelter Bureau) was established in MHA to oversee the implementation of the CD shelter programme. The MRT CD shelter was the first element in a comprehensive national CD shelter programme which included the installation of a network of public warning systems (sirens) placed at strategic points across Singapore to warn the public of imminent threats such as military attacks and disasters, both natural and man-made, that may endanger lives and property.



Civil Defence Public Warning System

The Singapore Government decided on a comprehensive shelter construction programme, starting with the incorporation of shelters in future HDB developments. The CD shelters would be the most visible and effective way to protect civilians from the effects of air attacks and artillery shelling. They would also provide our people with psychological assurance.

From 1987, all new HDB developments would be built with CD shelters. Then, the plan was that approximately 1,000 apartment blocks would be constructed with CD shelters that would provide places for 489,000 people at the end of the five-year programme.

People living in existing homes did not have access to the shelter programme in new towns. Basements and underground car parks

served as provisional shelters in the interim as their intrinsic qualities offered some degree of protection.



Engaging Students on Civil Defence in an MRT Civil Defence Shelter

In 1990, three years into the five-year programme, the first few batches of CD shelters under the apartments of new towns were completed and ready for use. A mid-term review of the project found that the cost of constructing basements beneath HDB flats to be not cost effective. On the other hand, building the CD shelters in the void deck would take up space allocated for social needs of the residents. There was also no rental demand for the space for economic activities, with only about 20% of these spaces being rented.

Following this review, the Singapore Government decided to delink the shelter programme from the public housing construction programme. Instead of providing one shelter for every new block of flats, HDB would provide sufficient shelter space based on its anticipated peacetime usage. The decision was also taken to extend the shelter programme to other new government developments such as schools and community centres built in existing residential estates.

The 1980s thus marked a period where public “communal” shelters were built in new HDB estates, and in new public developments such as the nine underground MRT stations, when the opportunities arose. The trade-off between being pragmatic and in protecting

people was evident when the HDB public shelters were down-scaled to match the anticipated peacetime usage. This shortfall in HDB public shelters was somewhat compensated by the construction of public shelters in schools, community centres and other public developments. Such trade-offs in balancing the costs of constructing shelters, the practical concerns of peacetime usage of CD shelters and having adequate shelter protection berths for the population would continue into the 1990s.

1990 Kuwait War

In August 1990, Iraq invaded Kuwait. The Israel Defence Force knew that Iraq had Russian-made SCUD tactical ballistic missiles which could be fitted with chemical weapon warheads. The Iraqis had about 100 SCUD-B missiles and locally developed variants.

The Israeli Civil Defence Authority was faced with a dilemma. They had been building communal shelters since their Civil Defence Law was legislated in 1951. The law requires the building of CD shelters in all homes, commercial and industrial buildings. These CD shelters were designed to provide shelter in the event of an air attack over the populated areas of Israel. The short warning time of minutes from the alarm of missile attack was not sufficient for people to run to CD shelters for protection. The population was instructed to prepare a room in their home and to seal it up with masking tape for the protection of their family members.

Household Shelters

The multi-ministry Shelter Review Committee was set up in 1992 to review the effectiveness of our CD shelters and the basic shelter design and planning parameters, taking into account lessons learnt from the 1990-1991 Gulf War.

There was empirical evidence from conflicts in the Middle East, that modern buildings with reinforced concrete structures were very

resilient from the effects of bomb blasts. In the 1982 Lebanon War, the Israeli Air Force found that reinforced concrete buildings in Beirut took multiple hits from bombs dropped by the Israeli Air Force fighter aircraft and remained standing. The inhabitants of the rooms destroyed by the effects of the bomb would be injured or killed, but the walls would shield and limit injuries to inhabitants in the other parts of the building. The shielding effect of walls was an important protection measure.

Studies on the effects of various weapons on an apartment with a household shelter, and household shelter modules were done. The effects of an explosion with a minimum of 1kg to beyond 1,000kg of explosives were assessed via full-scale tests. The effect of overpressure arising from the explosion was well understood by the professionals. The standard formula to determine the distances at which different types of facilities could be built was established in the explosives safety standards of the UK, the US and NATO countries. The maximum pressure generated in an explosion is proportional to the cube root of the net explosive quantity (NEQ) of a warhead. This would mean that for a warhead with NEQ of 1kg, the lethal range from overpressure of blast is 2.3m. As the maximum pressure was proportional to the cube root of the NEQ, the lethal distance for a warhead with 1,000kg NEQ is 23m, that is, only ten times that of an explosion with 1kg NEQ.

The secondary effect of an explosion had proven to be much more dangerous than the primary effect of overpressure on humans. Normal glass windows will shatter at a range of 33.3m from the explosion of 1kg NEQ. This is increased to 333m for a warhead with 1,000kg NEQ. Large-scale testings were performed in Singapore at Pulau Senang with up to 100kg explosive, and in joint testing programmes with Australia on the effect of the explosion of up to 40,000kg on buildings and glass windows at various distances.

Computer models were developed to simulate the effect of blasts and these models were then validated through large-scale testing.

The Shelter Review Committee recommended that shelters should be built to cater to a wide range of threat scenarios, including the need to consider chemical and other threats such as missiles, as the possibility of such weapons being available in the region in the future could not be excluded. To cater for an emergency scenario of very short warning time, household shelters would be the most effective form of sheltering protection as they are deemed as “scenario-free” and are readily accessible by the residents.

Our requirement would be to provide protection to our population that could deal with threats from a small number of SCUD-type of tactical ballistic missiles to a much larger number of cheap pipe rockets at the lowest cost. This would complement active air defence cover that would be provided by the RSAF.

The methodology used in the determination of operational requirements was operations analysis. We studied all the published reports of recent wars and conflicts to be kept up to date on how threats were evolving. Dumb aerial bombs might still be used in large numbers on targets that were well hidden from observation. Precision-guided munitions with circular error probable (CEP) of 2m, like laser-guided bombs, would be expected to be used against military targets. This would mean less collateral damage on civilians. Tactical ballistic missiles could be used but the number would not be large. Unguided rockets launched from cheap PVC pipes by the Hezbollah in Lebanon on the towns in the north of Israel and by the Hamas from Gaza are threats that are very difficult to eliminate.

The concept to decentralise protection to every home instead of having large communal CD shelters would be a robust

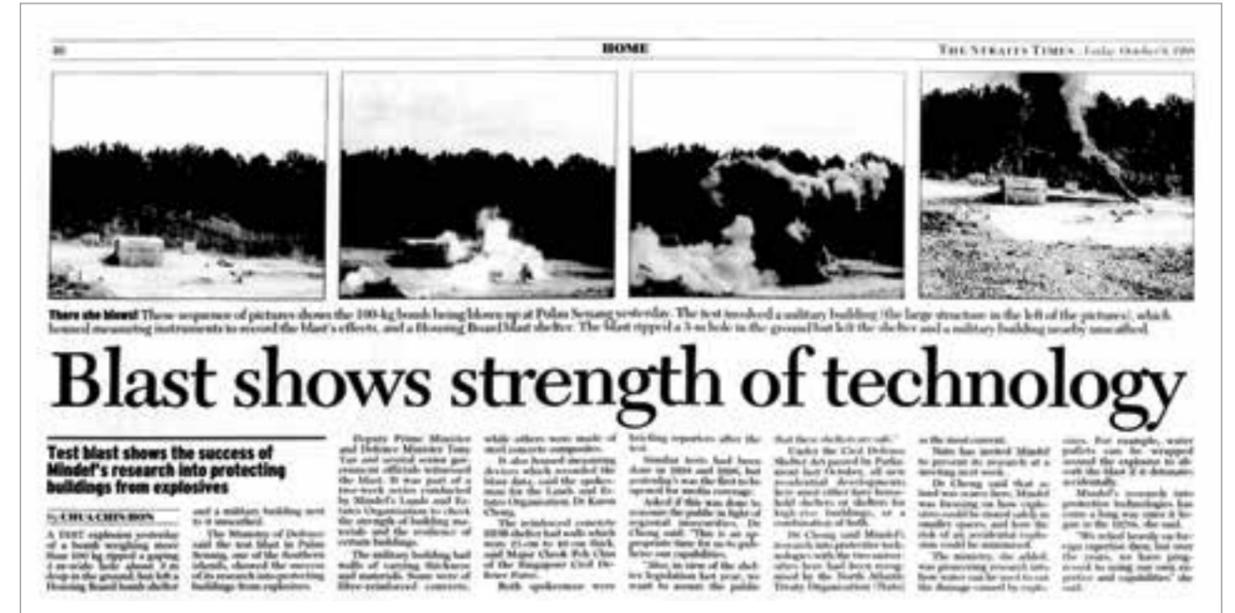
solution for our country. The validation of the design of the household shelter began with computer simulation, finite element modelling, laboratory testing, small-scale testing and finally full-scale testing. The first full-scale testing of structural elements and glass windows took place in 1994 at Pulau Senang. Complete units of household shelters were built and tested at Pulau Senang in 1996, 1998 and 2004.



Explosive Testing in 1998 Witnessed by then DPM Dr Tony Tan Keng Yam (second from left)

The UK Explosive Storage and Transport Committee and the Australian Defence Science and Technology Organisation were planning to do a full-scale explosion with 40 tons of explosives in 1999 and invited Singapore to participate. Other nations participating were Norway and the Netherlands. This was a great opportunity to collect data on the blast pressure and the amount of debris at different distances to the centre of the explosion. A representative dwelling was built and fitted with windows of different sizes and type of glazing. By participating in the trial, we also gained insights on the explosion effects from the experiments that the other countries performed.

Our tests confirmed that the greatest hazard to our people from weapons to be the secondary effects of glass fragments. The tests also confirmed that with proper “hardening”, glazing would not shatter at a range of 33.3m from the explosion of 1kg NEQ, as observed



The Straits Times report on full-scale explosive testing, 9th October 1998
Source: The Straits Times © Singapore Press Holdings Limited. Permission required for reproduction

for “normal” glazing.

On completion of the household shelter design, test and evaluation programme, our engineers were able to assess that the occupants would be completely protected from shattering glass and shrapnel from the warheads of bombs and missiles that the shelters were designed against. The shelters were also able to fully protect civilians from the hazardous effects of artillery shells and rockets, and partial protection from the over pressure from 1,000kg of high explosive at varying distances.

The Singapore Government accepted the recommendation of the Shelter Review Committee to require the construction of household shelters in all new HDB apartments. The construction of communal shelters at the foot of HDB blocks was thus discontinued. It also decided to introduce legislation to require similar shelters to be provided in new private houses and flats. The Civil Defence Shelter Act (CDSA) came into effect on 1st May 1998 requiring compulsory provision of shelters in all new residential developments.



Explosion trial in Australia involving 40 tonnes of TNT in 1999

ROCK CAVERNS FOR AMMUNITION FACILITY

Turning Dream into Reality

"Because they dared to dream, think deep and break new ground, we have created more space for our defence, while freeing up more land for Singapore."

Mr Teo Chee Hean, then Minister for Defence, at the Commissioning Ceremony of the Underground Ammunition Facility on 7th March 2008.

The Underground Ammunition Facility (UAF) is a story of dreaming, daring and doing.

The DSTA and MINDEF team envisaged a bold solution to build a first-class UAF in Singapore in an effort to find a solution to our land constraints. The team dared to challenge the norm, overcame many engineering challenges and became a first mover in the use of rock cavern space in Singapore. The result is state-of-the-art UAF.

The UAF provides superior protection for the SAF's war assets, and greatly improves safety and operational readiness. The development of the UAF opened up a new frontier in

space creation in land-scarce Singapore by achieving land savings of more than 300ha. In the process, DSTA set new standards on ground shock for underground ammunition storage safety which have been accepted by the NATO. NATO's standards on ammunition storage guide the development of such storage by its member countries, including established militaries such as the US, the UK, and France. We also developed a new competency in cavern facility development that has been put to great use to serve MINDEF and major national initiatives in underground space development.

Background

Seletar East Ammunition Depot (SEAD)

The Seletar East Ammunition Depot (SEAD) was one of the Army's ammunition stockpile depots. It was an ex-British depot located within the Seletar Camp. The depot was not optimally designed in terms of land use, and had the potential to be developed into a depot with much greater capacity. This could be done without increasing the hazard circles sterilised by the original depot.

In line with the national development plan, the Seletar Camp was earmarked for residential development by the year 2010. This would result in MINDEF losing one

of its strategic dispersion locations for the Army's ammunition stockpile. The need to relocate SEAD became one of the major considerations in the planning of ammunition storage facilities.

Looking Underground

The search for a new ammunition depot site in Singapore was not a simple task as a new depot would not only physically occupy a large area of land, the explosion hazard zones (yellow and purple circles) imposed by it would also constrain the surrounding developments. SEAD occupied a footprint of 109ha then and imposed a yellow circle (sterilised land) of 310ha and a purple circle (requiring glazing control) of 830ha. As a replacement, the new site must meet MINDEF's strategic considerations such as strategic dispersion in relation to the other existing depots, and it should also have the same potential capacity as SEAD to meet MINDEF's long-term storage requirement.

From 1991 to 1993, NTU and PWD jointly carried out a project to study the feasibility of constructing rock caverns in the Bukit Timah Granite. This study provided very positive input on the feasibility of cavern construction. With this, URA in 1994 suggested to MINDEF to consider siting the new depot underground at one of the disused quarries.

The feasibility of developing underground ammunition depot was in fact studied by MINDEF in the 1970s. However, the explosives safety standards of the UK that were adopted then were very conservative with regard to underground storage. As the construction cost for an underground ammunition facility was thought to be considerably higher, there was no economic advantage for constructing an underground ammunition facility, despite the intuition that we should have one.

MINDEF, however, agreed to URA's suggestion to reconsider the underground option in view

of the recent development in both research in underground ammunition storage safety and rock cavern construction technology. A Swiss consulting firm, Heierli Consulting Engineers, was engaged by MINDEF to carry out a study on the existing state-of-the-art technologies then for the development of the underground ammunition depot. The study also aimed to explore the technical and economic feasibility of developing underground ammunition storage depot at three quarry sites.

The joint study by MINDEF and the consultant, completed in early 1995, gathered that the knowledge base for underground storage had significantly increased over the previous 5 to 10 years. The study concluded that it was technically and economically viable to construct an underground ammunition storage depot at the disused quarry sites.

In addition to reduced land use, underground storage also offered many other advantages over aboveground storage such as improved safety, better security and protection against external threats, and lower maintenance cost. Given these added advantages and with the conclusion of the consultant's study, the Mandai quarry site appeared to be the best option as the replacement site for SEAD.

In February 1995, MINDEF approved the exploratory development of the UAF, and thus began the planning and technical studies that subsequently led to MINDEF's approval for the full-scale development of the UAF in 1998. The groundbreaking ceremony on 12th August officiated by then Minister of State for Defence, Mr David Lim, marked a major milestone in UAF development and a new approach to land use in Singapore. On 27th July 2001, MINDEF celebrated the completion of Phase 1 of the UAF excavation works. The completion blast ceremony was officiated by Dr Tony Tan Keng Yam, then Deputy Prime Minister and Minister for Defence. In March 2008, after more than 10 years of planning and development, the UAF was completed



The UAF was commissioned by then Minister for Defence, Mr Teo Chee Hean, on 7th March 2008

and officially commissioned by Mr Teo Chee Hean, then Minister for Defence.

Identifying the Technology Gap

The design of an ammunition facility is largely based on safety requirements in case of an accidental explosion, in addition to meeting user and operational requirements. The effects associated with an accidental explosion include ground shock, air blast, debris, and fire and heat at the tunnel exit.

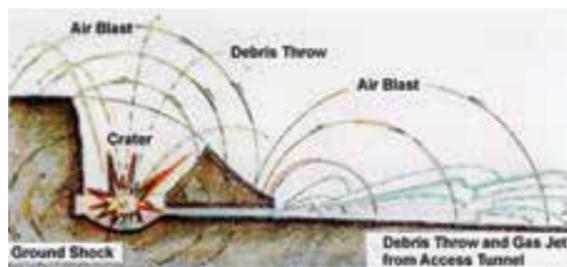


Illustration of the effects of an underground explosion (section view)

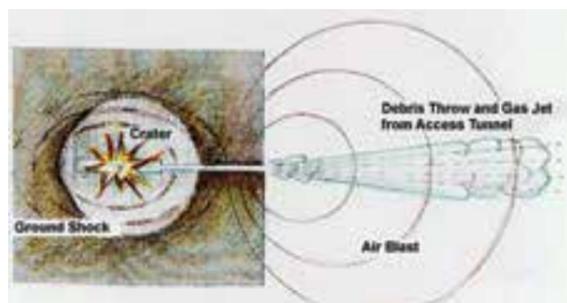


Illustration of the effects of underground explosion (plan view)

Ground shock refers to the shock waves transmitting through the ground, in a way similar to an earthquake, which may cause nearby buildings to crack or even collapse. Air blast refers to the shock waves propagating through the air, which may break glass windows and damage surface structures. Debris hazards are usually associated with the air blast, and refer to high-velocity fragments from the explosion, including fragments from the exploding ammunition and other fragments such as concrete and rocks from the venting tunnel and possibly rupturing rock cover.

The most common practice in addressing these hazards is by the use of land, keeping a safe distance from the source of explosion. This distance is defined largely based on empirical relationships between the maximum possible quantity of explosives in an explosion and the level of acceptable damage. These distances and air blast pressures form the basis of the safety criteria.

Safety and design codes existing in the western countries then were typically represented by those from the US DoD Explosives Safety Board, the UK Explosive Storage and Transport Committee (ESTC), and NATO. These codes specified the necessary safe distances and other requirements such as overburden thickness, storage chamber separation and basic tunnel design. However, because of the highly uncertain nature of an accidental explosion which might involve tens or hundreds of tons of explosives, and partly because of the lack of data on such large explosions, these codes tended to be conservative. While these codes might be acceptable in other countries, they were too conservative for some, especially land-scarce Singapore. An enormous amount of land would have to be sterilised in order to satisfy these safety requirements.

Motivated by the political issue of the US military storing ammunition in ROK without meeting the safety distances specified in the DoD Explosives Safety Manuals, the US and the ROK in 1991 started a five-year joint R&D programme to develop new technology for underground ammunition storage. This programme, costing a total of US\$13 million, was undertaken in an effort to reduce the vast amount of land that was being sterilised in US ammunition facilities in the ROK, with special emphasis on air blast reduction. Methods that had been studied included mainly geometric features (expansion chambers and sharp turns) and a closure device for the storage chamber (a concrete plug). The results had shown these methods to be highly effective

in air blast reduction. This programme then represented the state-of-the-art in underground ammunition safety. However, many problems still remained unsolved, in particular the issue of ground shock which was not addressed in the US-ROK joint R&D programme.

Given the high population density and extremely high land cost in Singapore, there was a need to design the UAF to minimise land use through technology. As such, we embarked on a major technology review effort which included reviewing the most commonly used codes, visits to and discussions with various government agencies and research organisations in the US, Norway, Sweden and Switzerland. Information related to underground ammunition safety was collected and analysed. The main objectives were to identify predictive measures that might be applicable to Singapore, to identify technology gaps, and to make recommendations for further R&D that would help remove these technology gaps.

The main conclusion from this effort was that significant technology gaps did exist for underground ammunition storage safety. There were also significant discrepancies among the existing codes, with many of the codes' specifications overly conservative for application in Singapore's context.

Ground shock remained the most uncertain aspect. Some of the reasons were actually pointed out in a paper by Mr Robert Odello of the US Naval Civil Engineering Laboratory in 1980, which referred to the possibly erroneous data source that was used for the equations for ground shock distance adopted by all of the four codes reviewed. Even if we accepted the data used for deriving the ground shock prediction equations, the classification of all soil and rock types into three broad categories by these codes were just too general and necessarily entailed additional conservatism. The problem was compounded by the damage criteria which were used to

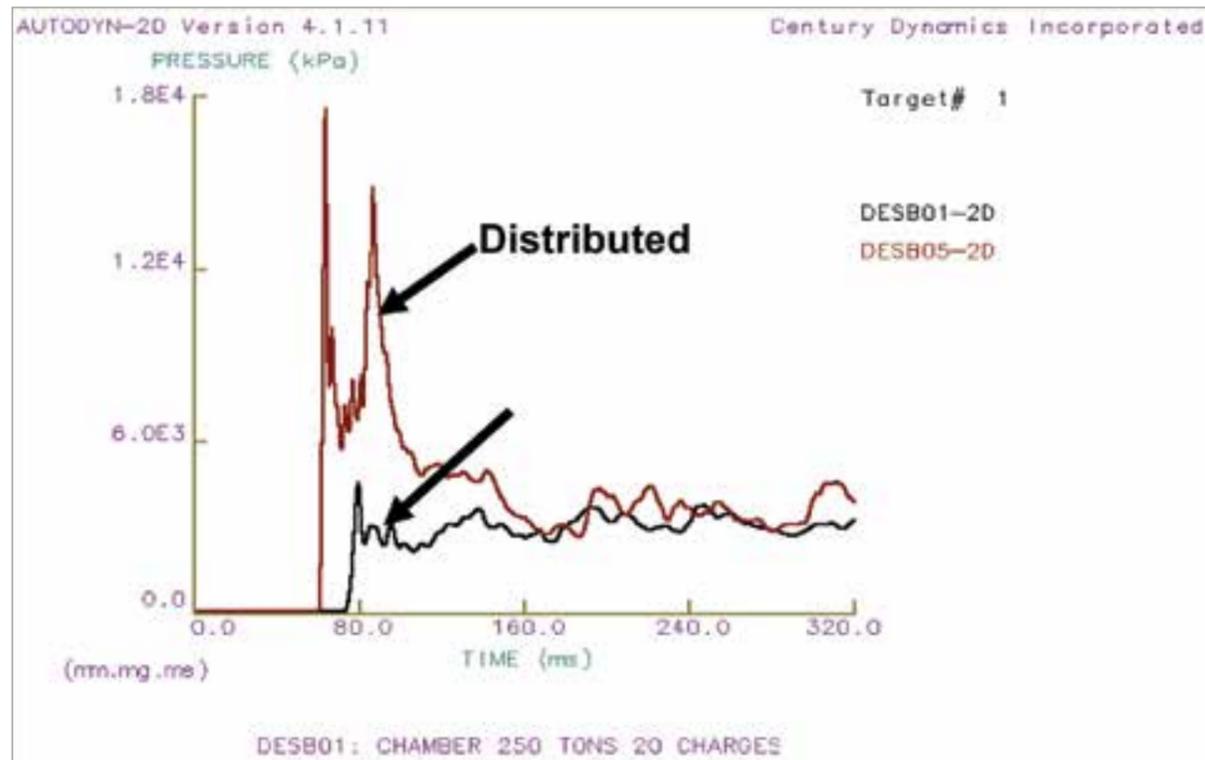
form the safe distances for ground shock. Most experts agreed that these criteria were based on data from the mining industry for claims against damage to wooden and masonry houses, whereas typical residential buildings in Singapore were of reinforced concrete. Finally, it was also realised that the ground shock equations and damage criteria were not adequate for applications in Singapore, due to our unique geological conditions.

Technology Development Programme

In order to resolve these critical issues related to underground ammunition safety, we embarked on a comprehensive technology development (TD) programme to minimise land sterilisation required while achieving a safe and economic design for underground ammunition facilities. The main objectives were to develop a set of safety and design criteria for such facilities and new technologies that could significantly reduce land use. This decision was made because there were no existing codes that would allow an efficient and economic design for our facilities, and no one else could decide the safety criteria for Singapore as these involve the safety of our people. We had to decide for ourselves.

The TD programme comprised three main components. The first concerned the development of more accurate prediction equations for ground shock, and revision of existing damage criteria. This component was mainly to resolve and remove the uncertainties and conservatism in the existing codes. More accurate prediction would allow for less conservatism and give us more confidence in our design. This would involve the development of computer models for the accurate prediction of ground shock based on Singapore's unique geological conditions and in-situ ground shock measurements, and the introduction of new damage criteria for modern buildings in Singapore.

The second concerned the reduction of



Significantly lower chamber blast pressure on blast doors from distributed charges compared to a single charge of the same mass, resulting in significant savings in blast door design.

maximum quantity in an explosion. Existing codes stipulated the use of the maximum possible NEQ in calculating the safe distances. This would entail two sources of conservatism. First, from experience, only a portion of the maximum NEQ would go off in an accident. Second, because of the way ammunition are cased and stored, the total energy imparted to the surrounding medium from this NEQ would be less than that from explosions of bare charges. Therefore, the main objectives of this component were to reduce the maximum NEQ that could actually explode in an accident, and the NEQ that would enter into the equation to calculate the safe distances.

The last part of the programme aimed to further reduce land use by reducing the effects of an explosion. The main objectives were to develop innovative technologies that could be used to reduce air blast and ground shock propagation, including the use of decoupling material for ground shock and

water mitigation. The use of water would also help solve another major safety and operational problem – heat and fire.

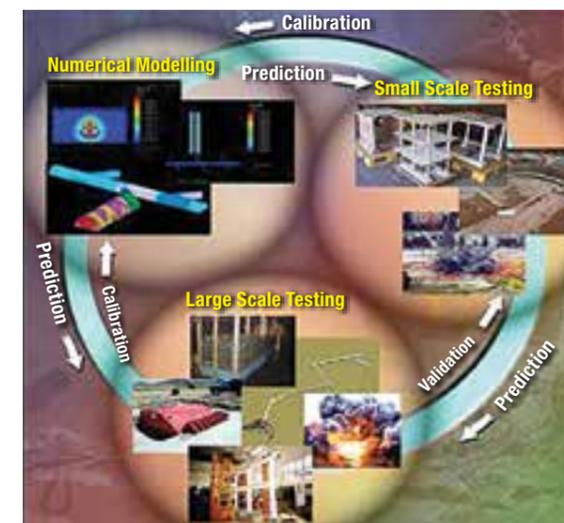
The TD programme was implemented using a feedback loop consisting of the following three components, namely numerical modelling, small-scale and large-scale tests.

The rapid advances in computing technology in hydro-dynamics have made it possible to realistically model complex problems. Calibrated numerical models could be used to perform parametric studies without having to conduct expensive tests, and provide final prediction of the explosion effects with better accuracy and ability to account for many design factors which simple empirical formulas could not. One major concept in explosion modelling introduced by the team was modelling the explosions in distributed charges compared to the traditional approach of modelling explosives as a single charge. A configuration of distributed charges would be

more realistic for ammunition storage and would result in a lower blast pressure compared to a single charge of the same mass.

Small-scale tests were used extensively to obtain data to calibrate numerical models based on actual design layout. They were also used for parametric studies and design verification of large-scale tests.

Large-scale tests were conducted for key safety components and design layout to validate blast loading and performance of structures and safety features in the tunnel system. These tests served to provide the final validation and large-scale data for validation of our numerical models.

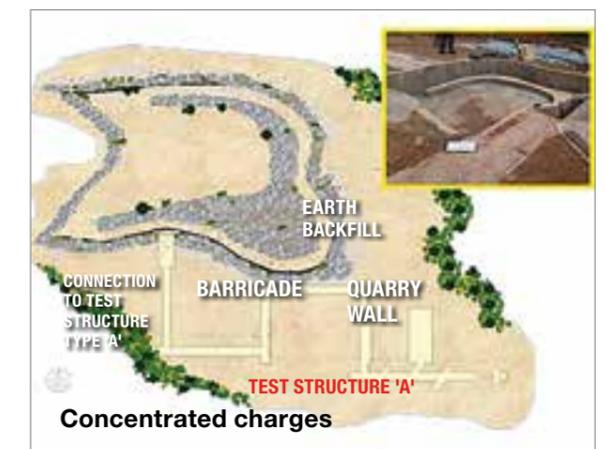


Systematic approach to technology development following a feedback loop for numerical modelling, small-scale testing and large-scale testing

In designing this TD programme, a three-pronged approach was used, depending on the objectives, availability of resource and time, and our desire to maintain MINDEF's technology edge. The three approaches were to conduct joint R&D with local universities and foreign agencies, as well as to procure specialist studies.

Local R&D projects took advantage of local expertise and lower costs, with the aim of

developing the technology and expertise in the local defence eco-system. These projects were mainly undertaken in co-operation with NUS and NTU. The involvement of DSTA engineers was an essential part of these projects. Projects undertaken in collaboration with foreign agencies took advantage of expertise developed in major R&D efforts over many years and sophisticated testing facilities available. They provided MINDEF and DSTA exposure and access to worldwide expertise and existing knowhow. They also allowed us to enter into large development projects with reduced risks through parallel research efforts and cost-sharing for large-scale tests. Specialist studies were used when the requirements for specific information or data (such as feasibility studies, computer modelling to verify a particular design) could be obtained from commercial organisations. Such studies, which could be conducted in a short period of time, would have taken a long time if we had done it ourselves as we needed to develop the necessary capability first. While executing the TD programme, specialist studies were sometime conducted before deciding on the subsequent R&D activities.



Layout for small-scale tests including key features of the tunnel system and external barricade and quarry walls

Large-scale Tunnel Testing

A series of five large-scale tests for the UAF tunnel system was carried out as part of a joint work programme between MINDEF and the Swedish Defence Research Establishment (FOI) between 2000 and 2002. The tests were designed to validate the safety design concept and explosion loading parameters for the UAF. Pressure measurements were obtained inside and outside the tunnel to characterise the blast environment, and ground shock measurements were made to study ground shock propagation and to examine the response of the adjacent chamber.

The test facility in Sweden was excavated in hard rock with similar rock mass properties as the UAF granite rock. The layout for the tests was based on a simplified layout of a typical storage cluster of multiple chambers and tunnels. It consisted of a detonating chamber, branch tunnel, two dummy branch tunnels, a main tunnel and an access tunnel. There were two 90°-turns in the tunnel system. Debris traps were constructed opposite the chamber and at every sharp turn. In addition, a slot tunnel of about 2m-wide parallel to the chamber was constructed at criteria chamber separation distance from the explosion chamber. This slot tunnel was used for monitoring the response of an adjacent chamber.

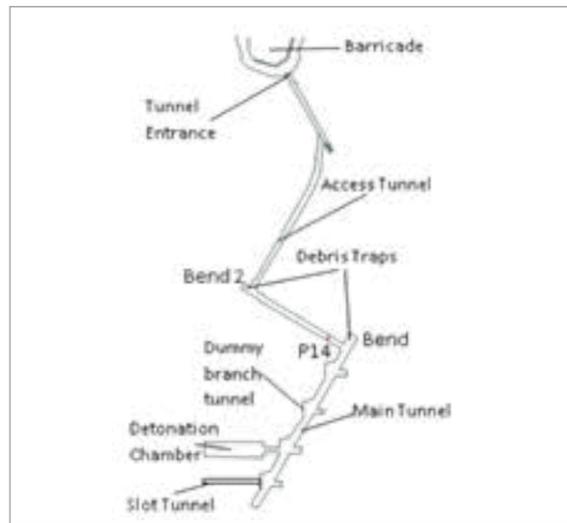
A total of five tests were carried out with various test objectives and storage conditions, including bare TNT charges as reference and for calibration, cased munition as worst-case scenario in debris hazards, and mixed cased munitions and propellants as typical storage conditions.

The explosive setup for the three bare charge tests with charge weights of 500kg, 2,500kg and 10,000kg TNT were evenly distributed into 10 cubes and placed with its centre of charge 900mm from the chamber floor. All the 10 cubes were detonated simultaneously

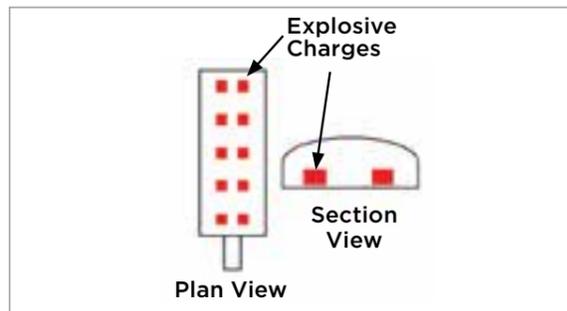
by ensuring that the length of the detonation cord from each cube to the booster charge was equal.



Fireball at the entrance tunnel of the large-scale test in Sweden



Layout of the test facility based on a simplified storage cluster with the key tunnel and safety features



Setup for explosives with distributed charges to simulate realistic storage conditions



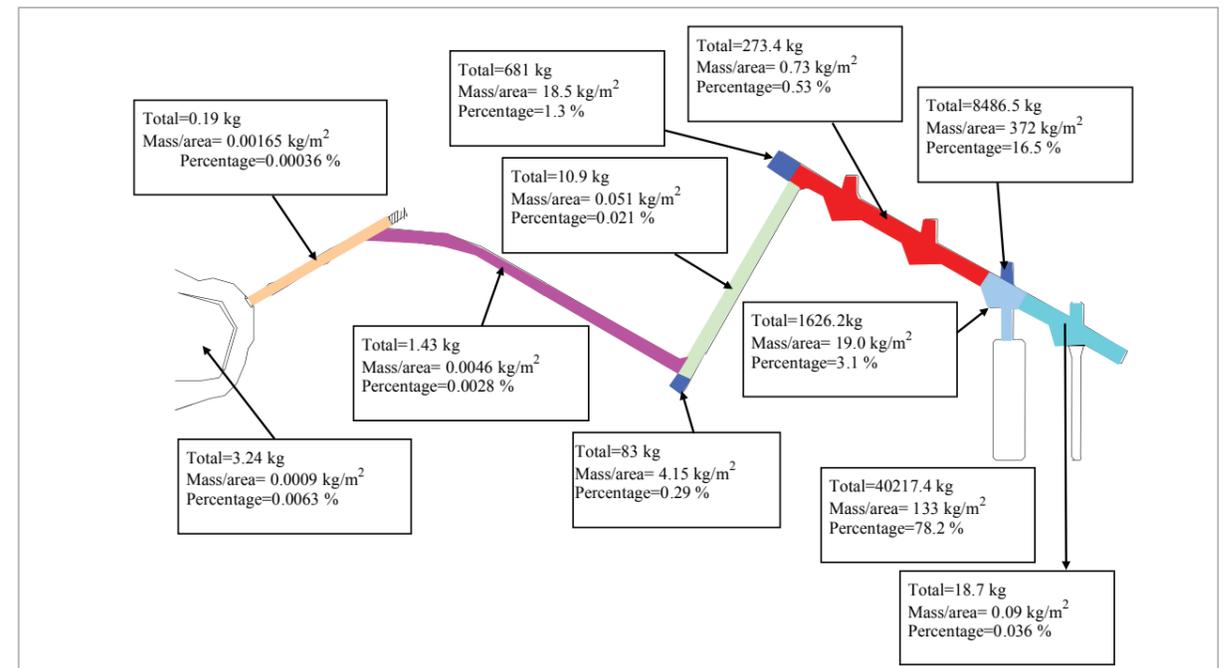
Setup for the bare charge tests to serve as the reference for comparison of explosion effects in air blast, ground shock and debris hazards



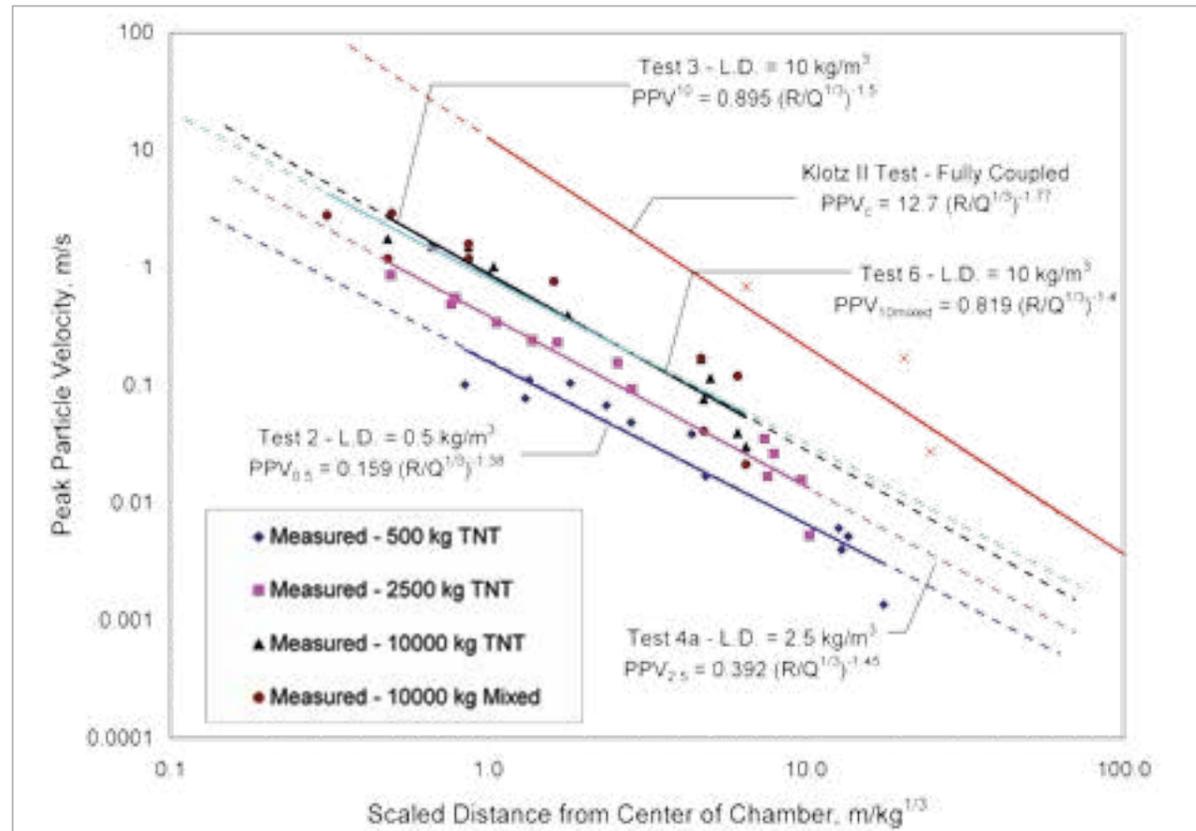
Setup for cased charges with 155mm artillery rounds to represent the worst case scenario for debris hazards

The large-scale tests enabled us to successfully validate the design of the UAF. Results of the validation tests were used in the final design of the UAF and helped achieved a cost savings of more than S\$10 million. The tests also provided the necessary and very valuable ground shock data for the validation of our predictive model for ground shock, which were subsequently used in developing the ground shock safety criteria.

The first of the series of tests conducted in Sweden in 2000 also achieved another first – the first such test to be conducted in the cold winter month of December. Luckily for the test team, it was also the warmest winter in Sweden in more than 240 years. Our Swedish partner strongly advised postponing the tests as they, based on past weather pattern, had expected the test site to be covered with snow and hence not suitable for test. We decided



Large scale test results from case charge test showing the distribution of debris mass inside the tunnel and the effectiveness of debris traps in reducing debris hazards



Large-scale test results showing the effects of decoupling on ground shock. These results provided major input in the development of the revised ground shock criteria for underground explosives storage safety

against their advice and proceeded with the test preparations as the postponement would have caused several months of delay to the entire test programme. Miraculously, the weather had worked to our favour! Heavy snow fall only arrived the day after the completion of the test.

Blast Door Testing

While some tests in Sweden were conducted in cold winter, the validation test for the chamber blast door was carried out in the warm desert of New Mexico, USA.

The chamber blast door was the key to the safety design to limit any accidental explosion to a single event by preventing propagation. It was designed to protect the contents of adjacent chambers from the effects of an explosion in another chamber. The blast door

test was carried out in collaboration with the DTRA of the US DoD. The test prototype was a one-half scale door element. The High Explosives Simulation Test (HEST) was used to simulate the required blast loading. The door was tested to half the design load, the full design load and two times the design load. The objective of the test was to verify the design and response of the door at various load cases, to verify the door design methodology including numerical simulation assumptions, and to identify any shortcomings in the design and failure modes. The test results were then used as input for the final design and analysis of the chamber blast door.

Developing a Robust Concept

The planning of the UAF development placed great emphasis on the development of a robust concept which would guide all

Shot	Load	Objective	Test
1	Calibration	Calibration	Bare Charge
2	Under load	Verify elastic behaviour	HEST
3	Design load	Verify structural response at design load	HEST
4	Over load	Verify structural response at close to failure load	HEST

***HEST - High Explosive Simulation Test**

Validation of chamber blast door at half-scale using HEST, conducted in New Mexico, USA

subsequent planning, design and technology development work. The final concept that would be adopted for the UAF must be the product of the best thinking and best practices among the international community, tailored to Singapore's unique conditions and constraints. To do this, we decided to conduct three different conceptual studies.

Getting the Best Practices

In order to provide MINDEF with the most comprehensive input, we conducted three separate conceptual studies to obtain the best practices from around the world. The rationale for this approach is described below.

First, although we were gradually building up our capability and expertise, we still did not have the experience or the expertise in the development of a large underground ammunition storage complex. Inputs from experienced consultants were considered essential to develop our conceptual design.

Second, there were two significantly different types of safety criteria for underground ammunition storage, each having its advantages and disadvantages. The first type was the conventional deterministic method which specified a safety distance based on a certain quantity of explosives (Quantity Distance, or Q-D) as safety measures, and was simple to implement. Usually storage by compatible groups would be required although some countries would allow varying degrees of mixed storage in underground facilities. This was what we had adopted so far for all our surface storage facilities. The second type was the risk-based method which provided more flexibility and allowed mixed storage, thereby enhancing operational readiness and space utilisation.

Although the risk-based method was gaining popularity in other countries, full conversion to risk-based approach was seen as difficult and would probably take a very long time to implement. As a result, most countries who were adopting the risk-based approach were

only using it to supplement their existing Q-D based criteria, to exploit the benefits of both methods.

Finally, different countries seemed to adopt different engineering solutions based on their unique conditions and experience. For example, while Switzerland used the Klotz Device¹ extensively in its underground ammo facilities, Sweden did not use the Klotz Device at all although it had more than 50 underground ammunition facilities. This significant difference was very much related to the safety management concept. In the Swiss risk-approach, a closure device that was normally in a closed position would result in much lower risk calculations than one that was normally in an open position. In the Q-D approach, a fixed reduction of the safety distance would be given, and it would make no difference in the Q-D distance whether the closure device was normally in a closed (e.g. Klotz Device) or open position (e.g. US/ROK Block).

Such differences in concepts and safety practice would have a significant impact on the operations of the proposed UAF, the safety management, and indeed the engineering solutions and cost of construction. In order for us to develop the most economical and efficient solutions for the UAF, we needed the best thinking from both “camps” and the most updated R&D information and technologies.

Three specialist consultants, Bienz, Kummer & Partner of Switzerland (BK&P), Sycon (formerly Confortia) of Sweden, and Engineering Research and Development Center (ERDC) (formerly Waterways Experiment Station) of the US Army, were identified to represent the best thinking in their respective fields, to help us achieve these objectives through three independent conceptual studies.

¹ Refers to a device such as blast door or concrete plug for containing explosion effects.

Three Conceptual Studies

Switzerland was the first country to introduce and fully adopt the risk-based approach for explosives safety. BK&P was the leading expert in ammunition safety risk management and was responsible for developing the Swiss risk-based approach. They had wide experience in safety planning and operations concepts in ammo facilities. Their solutions for the conceptual master plan based on the Swiss methodology and operations concept based on mixed storage represented a system that was very different from our practice then, but was the basis for many new approaches in ammunition safety management worldwide.

The main objective of the study by ERDC was to tap on the state-of-the-art technology research and safety approach, consistent with our practice in ammunition storage. The ERDC solution, through its involvement in the five-year (1991-1996) US/ROK programme to develop new technologies for underground ammunition storage, and access to the latest R&D results and new technologies, represented the cutting edge of the deterministic approach. The US/ROK programme resulted in major revisions to DoD 6055.9-STD, the US Military Standards for underground ammunition storage. New technologies were also developed which helped reduce the hazard areas for air blast and debris. However, as there were no underground ammunition facilities in the US, ERDC’s engineering experience in this area was limited, and most of it had come from the US/ROK programme. Also, as ERDC is primarily a research organisation, its ability to provide complete engineering consultancy services was limited.

Finally, Sycon of Sweden was the strongest in terms of engineering experience in planning and design of underground installations in rock. The team assembled by Sycon represented the entire spectrum of underground ammunition storage, namely ammunition safety, rock

engineering and protective design. With its wide experience and expertise, the solutions it proposed would most likely be feasible from an engineering point of view. As an engineering consultant, Sycon would also be better able to advise us on cavern construction and technical installations. Additionally, Sycon was completing a comprehensive study for adopting the Swiss risk-based method for application in Sweden. It had developed individual modules for specific conditions in Sweden to supplement its existing deterministic safety code. Therefore, Sycon was uniquely qualified to provide some link between the risk-based approach and the deterministic approach, and to present the most complete picture that we needed in finally deciding on the optimum solution for Singapore.

Selecting the Final Concept

One challenge faced by the project team then was how to evaluate and select from the various possible conceptual layouts developed through three conceptual studies done internally by DSTA. This had to satisfy the need to minimise land use and, at the same time, provide the most economical and efficient solution while meeting the safety objectives.

Of great importance in the evaluation was safety, which was the governing factor and utmost concern. This was also directly related to land use. Solutions that improved safety usually seemed to reduce operational efficiency and probably cost more. On the other hand, more reliable and efficient solutions may require large land sterilisation for the safety of people and facilities in the surrounding area. Ultimately, we had to find a solution that would balance the various seemingly conflicting requirements for safety, land use, operational readiness, and cost.

The Analytical Hierarchy Process (AHP) was used to select the final concept design,

synthesised from the best ideas from the three concept studies and our internal studies. This was based on an elaborate set of evaluation criteria involving safety, operations, land use, cost and technology risks. One innovative approach in the AHP was the development of the criteria and their weight ranking through a series of workshops involving both the safety and operations people from MINDEF, the licensing authority, the various subject matter experts in DSTA, and the design consultant.

Development and Implementation

In addition to technology development, one of the most critical issues was the user’s requirements, i.e., Specific Operations Requirements (SOR). In conventional development projects, the SOR is often supplied by the user in the beginning, with some interactions with the project team during the planning and design process. It was, however, difficult for the user to develop the SOR for the UAF as it was a technology-push project where the user had no previous experience in its operations.

This situation called for a collaborative effort between the designer and user to develop the SOR. In this case, the project team initiated the process by presenting to the user the necessary information for, and the effects of these SOR parameters on the design. In turn, the user responded positively by implementing studies aimed at answering these questions. Subsequently, various conceptual layouts were developed by DSTA for simulation studies by the user. It is worth noting that the development of the SOR and the final concept for the UAF was developed in parallel and approved almost at the same time. This interactive process and parallel development of the SOR and conceptual design was made possible by the early involvement of all key stakeholders. The interaction matrix developed for the UAF planning provided early application of some systems engineering tools. It allowed us to see

how the rest of the UAF system was affected when an important parameter was changed and was very useful in many of our trade-off studies and evaluation of alternative options.

At the early stage of the UAF planning, it was realised that the underground rock cavern would become an important resource for space creation in land-scarce Singapore. A decision was then made to maximise the potential storage capacity while minimising land use, and plan for future growth. This

decision imposed some constraints on the facility layout as the project team would not have the flexibility in choosing the location and orientation of the storage chambers.

Finally, a project of this magnitude required external expertise in the specialised areas of rock engineering, ammunition storage safety and protective design, among others. This was partly because we did not have the required expertise, and partly due to limitations in manpower and time. It was also clear that

because of the project complexity, no single consultant could undertake the project on his own. He must rely on other consultants to carry out the specialised tasks. In other words, there was a need for a prime consultant; all other specialist consultancy services could then be done through this prime consultant on the basis of need.

Due to security considerations and the need to build up local capability, Sembcorp Design and Construction Pte Ltd (SDC), formerly Sembcorp Construction and MINDEF's strategic partner in construction was chosen to develop the facility. As SDC did not have any expertise or experience in this area, arrangement was made for it to build up its capability in the design and construction of underground rock cavern facilities through active involvement in the entire project.

A key strategy in the competency build-up was a pilot phase of the project involving the key technology areas and included determining the most likely geological conditions at the site. For this phase, both the design consultant and contractor from SDC were teamed up with specialists from overseas in joint ventures, for training and technology transfer.

Achieving Land Use Savings for the UAF

The UAF achieved direct land savings of more than 300ha as compared to the SEAD. The significant land savings was achieved through a combination of three key factors.

Inherent benefits of underground storage

In addition to the excellent protection it provides, the effects of an explosion in an underground facility can be better contained. These provide great potential for land savings. As such, a much larger amount of explosives can be stored in every chamber compared

to aboveground, and the chambers can be spaced closer together, giving rise to a smaller footprint for the same quantity of explosives stored.

Technology-Enhanced Benefits

In the UAF project, additional efforts were put into developing advanced technologies and innovative designs that further enhanced land savings.

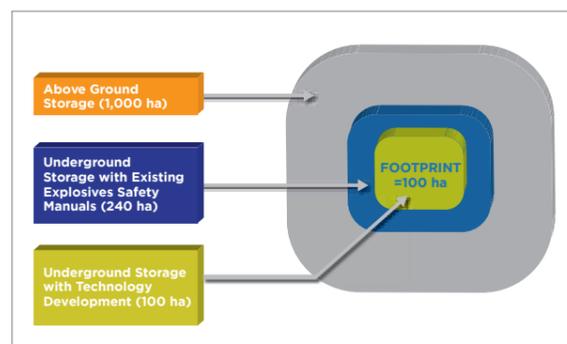
- More accurate prediction of the physical effects of an accidental explosion and response of structures allowed more precise definition of safety zones, thus avoiding unnecessarily conservative design. This was done through extensive numerical modelling and large-scale validation tests.
- Engineering safety designs that limited the damage in case of an accidental explosion. For example, interlocking chamber blast doors would limit an explosion to a single chamber.
- Engineering design features that would mitigate the external effects. One example is how multiple debris traps would minimise external debris hazards and reduce the air blast exit pressure - each debris trap would reduce debris amount by 90% and blast pressure by 20%.
- Expansion chambers in the tunnel system would reduce air blast exit pressure.
- A continuous portal barricade carved out from the granite would reflect air blast backwards and stop any remaining debris that might exit the tunnel system, thus further reducing the air blast circle and external debris hazard.

The following table provides a summary comparison of the land use and benefits of underground storage and use of innovative engineering safety designs for the UAF.



Using a systems engineering approach, an interaction matrix was developed for the planning of the UAF that allowed the project team to perform trade-off studies in a holistic manner

Storage / Technology Options	Land Sterilisation
UAF	100ha
Underground storage with existing safety manual	240ha
Aboveground storage of similar capacity ²	1,000ha



Achieving land savings for the UAF through underground storage, technology development, and innovative engineering design

Innovative Approaches to Rock Tunnelling

Due to the limited land space in Singapore, the use of underground space has to be optimised. This means that there is less room for flexibility when planning the tunnel and cavern layout. Hence, rock engineering was a key part of the development of the UAF.

The UAF was the first hard-rock cavern project in Singapore. A mature tunnelling technology known as the Norwegian Tunnelling Technology (NTT) was adapted

²The UAF was designed to replace the SEAD, but it could store much more when fully developed within the same land boundary. The 1,000ha is an estimate based on the assumption that at least two above-ground sites would be needed to develop a total NEQ capacity equivalent to the UAF master plan.

to the local context. The use and transfer of NTT was an essential part of the strategy to build local capability in rock tunnelling. While adopting the NTT, the project team implemented innovative approaches to rock cavern management, as well as risk management and contracting practice.

The NTT is a system of tunnelling practices and processes that encompasses a complete set of techniques for site investigations, design, construction and rock support. It adopts a systematic approach to the different phases of tunnelling, and follows principles of the observational method which include assessment of the variations in ground conditions, observations during construction and modification of design to suit actual site conditions. The success of this method also depends on close collaboration among the client, contractors, design engineers and engineering geologists.

Some of the key processes and techniques in rock tunnelling applied in the UAF project are discussed in the following sections.

Site Investigations

Unlike the construction of buildings, rock excavation involves working with uncertain ground conditions as the quality of rock mass cannot be determined until it is excavated. Moreover, cavern construction was relatively new in Singapore. To ensure that the site was suitable for construction and to obtain reliable data for design, site investigations had to be carried out. Site investigations were also essential to establish the three-dimensional (3D) geological model of the cavern, which included the rock head elevation, major geological features and the distribution of rock mass properties.

Extensive site investigations were carried out using a combination of modern geophysical methods, diamond core drilling, laboratory and in-situ testing to assess the site conditions

and rock mass quality. These activities formed an integral part of the engineering design process, which considered aspects such as the layout plan, rock support design, cost and construction safety. Complementary methods were used in combination in order to minimise uncertainty in the data obtained.

A three-stage approach was employed for the UAF project:

- Preliminary site investigations to establish overall feasibility
- Main phase investigations based on selected method of tunnelling
- Supplementary investigations during design and construction

The Use of Q-system for Tunnel Design

A key component of the NTT is the Q-system used for tunnel design. The Q-system is a design method based on the tunnelling quality index, Q. The index, developed by the Norwegian Geotechnical Institute in the 1970s, is based on the stability evaluation of a large number of case histories of underground excavations. The Q-system has gone through many rounds of update, and is the most commonly used method in the world for rock engineering design based on rock mass classification.

Based on the site investigation results, the rock mass is classified according to the Q-system for the preliminary support design. The actual support design is determined during construction, after the excavated tunnel surfaces are mapped and a final rock mass classification is done based on the tunnel mapping data.

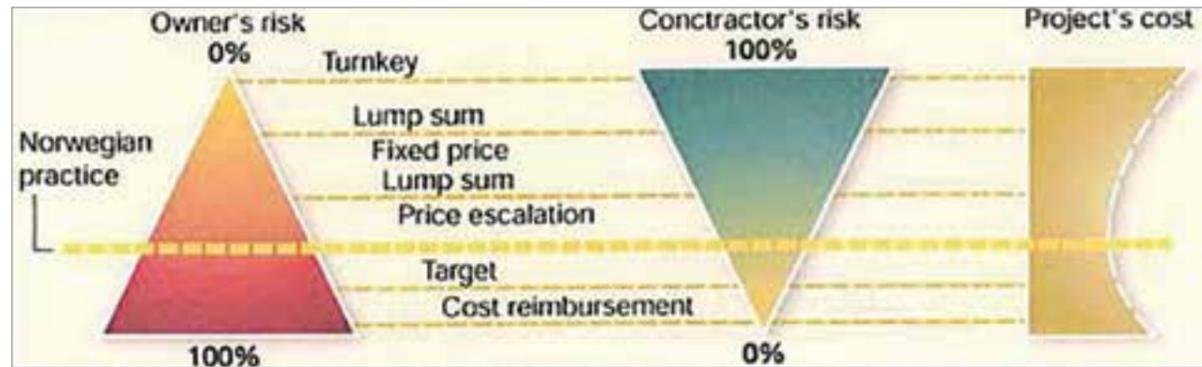
For the UAF project, the project team and the contractor agreed to adopt the NTT based on the Q-system as a guideline for estimating rock mass conditions and rock support requirements. This arrangement was considered a very important basis for

establishing a mutual understanding or a common “tunnelling language” among the project team, consultant, and contractor. It was also critical because local regulations did not have any design code for rock tunnelling. One key challenge of designing using the Q method was the statutory approval for structural design. Traditionally, the final structural designs for civil engineering projects must be approved before construction can begin. However, in the Q method, the final rock support design can only be decided after the rock tunnel is excavated, the exposed rock mapped and the appropriate rock support prescribed based on this mapping. The project team worked with the Building and Construction Authority (BCA) to adopt the Q method for rock tunnel design.

Innovations in Rock Engineering

While adopting the NTT to the local context, the project team had to address several unique challenges through innovation.

The lack of local expertise in hard rock tunnelling meant that the project team had to rely on foreign expertise and the subsequent transfer of technology, and establish collaboration with the contractor to manage these risks innovatively. Stringent regulations and control in Singapore on explosives posed challenges related to storage and transport of explosives for the blasting works in rock excavation. To ensure that safety requirements were met, the project team searched for new technologies in the market. The limited resources in Singapore spurred the project team to come up with sustainable initiatives that addressed the need for environmental protection. Thus, the innovative re-use of excavated rocks and pond water was explored. The project team also challenged the conventional methods in rock engineering design to maximise land use for the UAF development.



Norwegian concept of risk sharing for different contracts (Norwegian Tunnelling Society, 2008). Appropriate sharing of geological risks makes it possible to achieve the most realistic contract price

Winning Through Collaboration

Risk Management and Contracting Practice

The management of geological risks was given high priority for the UAF project. This included a comprehensive site investigation programme and various contractual arrangements aimed at minimising geological risks. Emphasis was also placed on facilitating technology transfer, as competency build-up within the local community was essential to minimise geological and security risks.

The rock excavation work was divided into a pilot phase and a main phase. The pilot phase was a small portion of the overall rock excavation work, but the site chosen for this phase represented the worst expected geological conditions. The pilot phase was conducted with the following objectives:

- Facilitate technology transfer and competency build-up
- Understand geological conditions and rock mass quality
- Evaluate effectiveness of excavation method and rock support
- Collate data on cost, unit rates and time
- Verify design assumptions and cavern performance through instrumentation
- Gather feedback for improving the design and technical specifications of the tunnel

From a risk management point of view, there were two main aspects for the project team to consider in the contractual arrangement. The parties involved in the contract had to decide how the geological risks would be shared, and to plan how the design and rock excavation would be managed.

The key concept adopted for addressing geological risks was contractual risk sharing. Under the Norwegian risk sharing concept, the client is responsible for the ground conditions, the site investigation results and the overall design concept while the contractor is responsible for the construction performance in accordance with specifications.

For the pilot phase and the main phase of the excavation work, the traditional Design-Bid-Build contract was adopted for the UAF project. This type of contract allowed more flexibility in dealing with the geological uncertainties during excavation. In this arrangement, the selection of consultants, approval of design and specifications, and the overall control of the project remained with DSTA (client), while the consultant carried out the detailed design.

Unlike the main phase, the pilot phase was based on a cost-plus or cost-reimbursement contract. The cost-plus contract was used due to the lack of local expertise and experience. This form of contracting also facilitated

technology transfer and provided the basis to determine the excavation work charges in the main phase. Using a cost-plus contract required very tight management and deep technical involvement by DSTA, as well as close collaboration among all parties working on the project.

Upon completion of the pilot phase, the client and contractor established a common understanding of the expected geological conditions and references for the various cost components. The main phase of the excavation was based on a lump sum Design-Bid-Build³ contract with unit rates established during the pilot phase. The advantage of the high flexibility was fully realised with corresponding contracts that specified a fair risk sharing between the client and the contractor. As a result, the rock excavation work went smoothly without any disputes while achieving very competitive cost rates for rock excavation.

Combining Aggregate Mining and Quarry Shaping

Shaping the Mandai quarry was an essential part of the design to ensure facility protection and external safety while providing access to the UAF. With nearly 30ha of surface area covering the quarry site, shaping the Mandai quarry required substantial rock excavation.

During the early stages of the UAF planning, the HDB was operating within the existing quarry to provide supply of aggregates for its housing projects. It wanted to continue its quarrying operations for as long as possible. The project team worked with the HDB Quarry Office to devise a plan that would allow quarrying operations to continue, while the quarry was shaped according to the requirements of the UAF project, including

³Design-Bid-Build is a project delivery method in which the agency or owner contracts with separate entities for the design and construction of a project.

excavation of the barricade driveway and use of controlled blasting to minimise rock damage for the final quarry walls. This inter-agency collaboration was a win-win approach that helped the project to save more than S\$2 million in rock excavation and quarry wall protection works, as well as reduce the construction lead time.



Combining aggregate mining by HDB and quarry shaping for the UAF

Excavating More for Higher Productivity

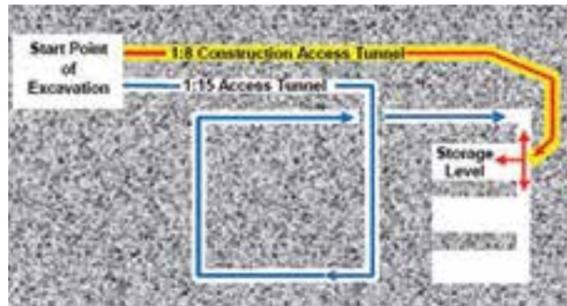
The drill-and-blast method is cyclical in nature and it is a slow process with the average blasting cycle advancing at a rate of a few metres in tunnel length per blast. For resources to be used optimally and the overall excavation time to be shortened, it is advantageous to excavate concurrently on multiple working faces.

Based on the facility layout, the contractor had to excavate the long access tunnel leading to the storage area where multiple faces could be opened for excavating a major volume of rock. However, this approach would result in longer excavation time and lower productivity.

To gain direct and faster access to the storage area and open up multiple working faces, the project team instructed the contractor to excavate a separate construction access tunnel with a steeper gradient. This construction access tunnel required the project team to work around the tight tunnel layout.

With the excavation of the construction access tunnel, the contractor was able to reach the caverns in half the time required and ramped

up the production rate by opening multiple working faces early. The time for clearing the excavated rocks away was also reduced because of the shorter transportation distance involved. This solution helped the project saved four months of construction time and resulted in overall savings of more than S\$1 million although more excavation works were done. This shorter construction access was also used for excavation in the main phase work.



The shorter construction access tunnel allowed faster access to the storage area to open up multiple working faces and improved tunneling resource usage and productivity

Harnessing New Technologies

The blasting work for the UAF excavation required thousands of tons of explosives. Due to the stringent safety regulation with regard to the use of explosives in Singapore, storing and handling the necessary explosives posed major challenges during the construction planning stage. The daily transportation of explosives for blasting work would also mean additional risks to public safety.

A new commercial explosive product called bulk emulsion was selected for use in the project. Through this project, this product was introduced for the first time in Singapore. The bulk emulsion is classified as a Class 5.1 Hazard Division chemical (non-explosive) and could be stored safely on site. The emulsion would become "live" after being mixed with an oxidising agent before it was pumped into the drill-hole.



On-site storage of bulk emulsion which goes "live" only after it is mixed with an oxidising agent

With the use of bulk emulsion, the only high explosives required for the blasting work were the detonators and the booster charges. To address the safety and logistic issues, approval was sought from the licensing authority to construct and operate a temporary on-site magazine to house the detonators and booster charges within the construction site, in a rock cavern excavated specifically for this purpose. This on-site magazine was the first of its kind to be built locally in a rock cavern to store construction explosives. As a result, transportation of high explosives on public roads was reduced from a daily to a monthly activity. Explosives could be drawn as and when required for the blasting work.



On-site storage magazine in a rock cavern for detonators and booster charges

The combined use of bulk emulsion and on-site storage of detonators and booster charges solved a major safety issue, and resulted in better productivity. The use of bulk emulsion also helped to reduce ventilation time and air pollution due to its less toxic fumes from

blasting. The total estimated cost savings was about S\$10 million compared to the use of traditional explosives and commercial storage. The introduction of bulk emulsion to the UAF project was such a success that the Norwegian Road Authority requested a visit to the UAF site to learn more about this new technology for their own evaluation process.

Turning Waste into Assets

The excavation work at the UAF generated about several million tons of excavated rocks, also known as muck or waste material. This large volume of excavated material had to be disposed of at a cost.

The project team came up with the idea to re-use the granite muck as a material replacement for graded stones in constructing pavements. The granite muck from the rock excavation was sieved on site to obtain a material similar to graded stones for use in road base construction. The recycling of sieved muck for road base construction achieved an overall cost savings of S\$860,000 for muck transport and buying of road base materials used in the UAF development.

Through an open tender, the majority of the excavated rock was sold to a contractor which processed the excavated rocks into various building and road construction products. The rock disposal contract generated revenue of S\$17 million for the government, while saving the UAF project the cost of rock disposal.

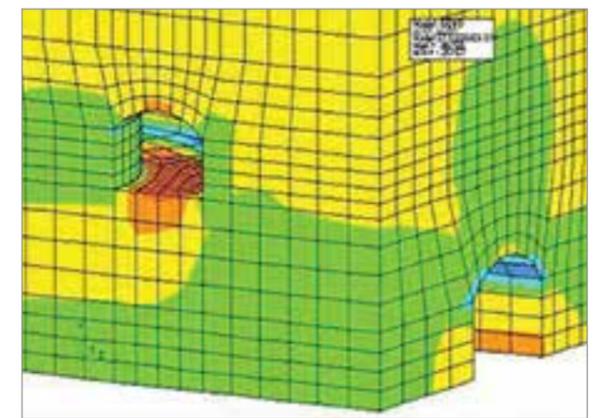
Challenging the Norm

With the need to minimise land use for underground ammunition facility development, one of the challenges faced during the planning stage of the UAF was to configure the underground space within a very compact footprint. To minimise the overall land use, it was important to obtain the optimal separation distance between tunnels. There was also the challenge to ensure that

excavation of the tunnels at close proximity would be safe and stable.

For the UAF project, there was a tunnel directly above another tunnel. The specialist consultant had proposed a minimum separation of 15m between the two tunnels based on the traditional guidelines. However, this separation would require deeper storage chambers, a larger footprint, and longer access tunnels resulting in higher construction costs and longer vehicle travel time for operations.

Through a research project with NTU, and working closely with the consultant, the project team was able to reduce the tunnel separation distance to 8m by taking advantage of the relatively high horizontal stress, resulting in cost savings of more than S\$9 million and a shorter transport distance for user operations. This solution was made possible through extensive numerical modelling of the tunnel configuration, supported by instrumentation to make on-site measurements.



Numerical modelling of one tunnel directly above another

International Collaboration

Since the implementation of the TD programme, we have continued research to improve the accuracy of predicting the intensity of ground shocks resulting from an accidental underground explosion, and the structural response to the shock waves

on the ground surface. Our work in this area has captured great interest amongst the international community of explosives safety experts. Since July 2000, DSTA has represented Singapore as a member and secretary of the NATO AC/258 Underground Storage Working Group (UGSWG) to review the Manual of NATO Safety Principles for Underground Ammunition Storage. Singapore is also a member of the Klotz Group, an international body of explosives safety experts working on safety issues associated with the storage, processing and transport of ammunition and explosives. Today, results of our work on ground shock have been incorporated into the Manual of NATO Safety Principles for Underground Ammunition Storage, AASTP-1 and the NATO Manual on Explosives Safety Risk Analysis, AASTP-4.

Membership with NATO AC/258 Underground Storage Working Group

Our first direct interaction with the NATO AC/258 UGSWG began when Singapore was invited to participate in a joint meeting it had with the Klotz Group in August 1998, at the 28th US DoD Defence Explosives Safety Seminar in Orlando, USA. At the time, Singapore had been applying for membership with the Klotz Group, which often held joint meetings with the UGSWG due to their common interest in ammunition storage safety. At the seminar, we presented preliminary results of our work on ground shock prediction and damage criteria which attracted the attention of the UGSWG as the latter was looking for updated research on ground shock. We held informal discussions about the possibility of Singapore participating in the UGSWG. At its invitation, Mr Ong Yew Hing and Dr Zhou Yingxin attended a special meeting of the UGSWG held in October 1998 in Huntsville, USA, to discuss safety criteria for underground storage with a focus on ground shock and the latest work done by Singapore. Singapore successfully became a member of the UGSWG in July 2000 under the

sponsorship of Norway, and was appointed the secretary of the Working Group and the lead nation for the area of ground shock with Norway as the supporting nation.



Singapore delegates attending a special meeting of the NATO Underground Storage Working Group in Huntsville, USA in 1998

Our membership in the UGSWG was made possible by our state-of-the-art research in ground shock safety criteria for underground ammunition storage and our excellent collaboration with Norway. One of the leading experts in NATO at the time was the late Mr Arnfinn Jenssen of Norway, who played an instrumental role in fostering close collaboration between Singapore and Norway, and in our membership with the UGSWG. We first met Mr Jenssen in 1995 during our technology acquisition activity for the UAF. Mr Ong and Dr Zhou visited him at his office at the Norwegian Defence Estates Agency (NDEA, then known as the Norwegian Defence Construction Service) to learn from his experience in underground explosive storage. After a few encounters with him, he became a good friend of ours and other Singaporeans who had worked with him.



Former CE DSTA, RADM (Ret) Richard Lim (eighth from left), with the project team and Swedish FOI partners at the tunnel site of the large scale tests in Sweden

Despite his standing in the international community, Mr Jenssen was always willing to share his knowledge and teach our young engineers. He was also very open-minded and ready to listen to our ideas. His personal stories were always fascinating to us, such as how he was captured by the Germans during World War II and later escaped, or when he had to carry loads of cash on his flight to pay for explosive testing in the USA. In 1997, we invited him to Singapore as the first MINDEF Visiting Scientist and accorded him the honour, hospitality and access to MINDEF top management. He worked the ground for us in Norway and among the UGSWG member nations, leading to the signing of the Letter of Intent in 1998 between the then LEO and NDEA that started the fruitful collaboration between our two countries in the areas of protective technology, explosive storage safety, and rock cavern technology.

The large-scale tests (LST) in Sweden and validation test of the chamber door in New Mexico, USA also involved collaboration with several foreign government agencies. The LST programme was carried out in collaboration with Sweden's FOI, the Swedish Armed Forces HQ and the Swedish Fortifications Administration, and was supported by the Norwegian' NDEA and the US' DTRA. The Klotz Group also contributed by providing technical advice during the planning and design, conduct of the tests and analysis of the test results. The validation test of the chamber blast door was done in collaboration with the DTRA. Singapore also collaborated with the Waterways Experiment Station of the US Army in conducting additional ground shock tests as part of the US-ROK testing programme.

From learners in the 1980s, we have gained international recognition for the good work done through the UAF TD programme. Today, DSTA is a recognised expert in the area of underground ammunition storage and a leader in the innovative use of rock cavern space.



The UAF team, comprising members from MINDEF, DSTA and Sembcorp Design and Construction, won the Defence Technology Prize 2007 (Engineering)

The UAF has won several prestigious national awards, including the Defence Technology Prize 2007 (Engineering) and the Institute of Engineers Singapore Prestigious Engineering Achievement Award 2004.



The joint DSTA and NTU team won the IES Prestigious Engineering Achievement Award in 2004 with the project on "Maximising Land Use in Singapore"

Contributing to Underground Space Development in Singapore

In response to the need to co-ordinate the national efforts in the use of underground space, URA formed a taskforce in May 1996 to explore possible uses of underground caverns and related implementation issues. The taskforce was led by URA, and consisted of representatives from MINDEF, the Ministry of the Environment (ENV) and MND, Housing & Development Board (HDB), Public Utility Board (PUB), Jurong Town Corporation (JTC),

Construction Industry Development Board and PWD. DSTA represented MINDEF in the taskforce. The taskforce completed its report in 1997. The report recommended a pilot project in view of the inadequacy of local experiences and support framework for underground caverns. As MINDEF was working on developing the UAF, the UAF project was identified as the pilot project.

Throughout the development stages of UAF, MINDEF, together with DSTA, actively promoted the use of underground space in rock caverns by organising visits to the UAF to share our experiences with other government and public organisations. These organisations included the Singapore Parliament, the Parliamentary Committee (Defence), the Pyramid Club, JTC, PUB, ENV, Powergrid, the Land Transport Authority (LTA), Ministry of National Development (MND), URA, the SCDF and the SPF. A technical session was even held in the UAF during the International Symposium on Defence Construction in 2002.

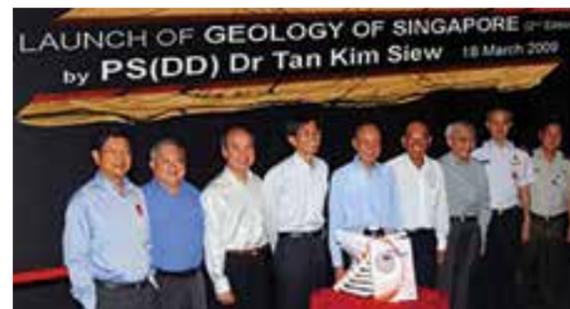
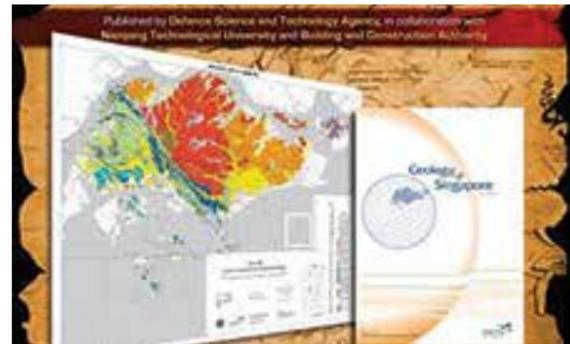


Technical session on underground facilities held in a rock cavern of the UAF during the International Symposium on Defence Construction organised by DSTA in 2002

The successful development of the UAF was significant for Singapore from a land use point of view. It demonstrated the feasibility and many benefits of rock cavern use and opened up a new frontier for space creation in land-scarce Singapore. The UAF achieved land savings of more than 300ha by going

underground, equivalent to half of the Pasir Ris New Town. The UAF also represented a major breakthrough in overcoming a psychological barrier on the use of underground space by many government agencies and provided many good learning opportunities.

In 2009, DSTA published the updated Geology of Singapore (2nd Edition) in collaboration with BCA and NTU, which was spurred in part by the development of UAF. This publication represents a major contribution by DSTA to the construction industry and geo-sciences community in Singapore.



The launch of Geology of Singapore (2nd edition) by then PS (DD) Dr Tan Kim Siew (5th from left) in 2009

Significant Milestones in the Development of the UAF

Date	Development / Milestone
1991 – 1993	First feasibility study by NTU and PWD on constructing rock caverns in the Bukit Timah Granite. NTU and PWD organised a public seminar in October 1993 to disseminate findings of the feasibility study. A briefing to the Ministry of Finance was conducted in September 1994.
1993-1994	MINDEF conducted a series of studies that established the technical and economic feasibility of constructing an underground ammunition facility in Singapore.
Feb 1995	MINDEF approved planning studies for the UAF. The planning studies included conceptual studies, site investigations, small-scale testing, ground shock testing in the US, and initial R&D projects with NTU and NUS.
May 1996	Formation of a taskforce on Underground Rock Caverns led by URA. The taskforce produced the “Report on the Use of Underground Rock Caverns” in 1997. In this report, the MINDEF UAF was identified as a pilot project.
June 1996	A large-scale ground shock test was jointly conducted with the Waterways Experiment Station in the Linchburg Mine in Socorro Country in New Mexico. Data obtained from the test were used to calibrate numerical models that were being developed for ground shock prediction in complex geology.
1997	Singapore – Norway Workshop on Cavern Technology jointly organised by then NSTB and the Norwegian Research Council.
April 1998	MINDEF approved the development of the UAF.
1998	Mr Arnfinn Jenssen of the Norwegian Defence Estates Agency, on behalf of the NATO Underground Storage Working Group, requested to use DSTA papers presented at the 1998 US DoD Explosives Safety Seminar as informal working papers for the Working Group.
12 th August 1999	Ground breaking for the UAF, officiated by the then Minister of State for Defence, Mr David Lim.

Date	Development / Milestone
1999	Singapore was invited by Dr Chester Canada of the US DoD Explosives Safety Board to join a special meeting of the NATO Underground Storage Working Group, where our proposal for new ground shock criteria was first discussed.
1999 – 2001	NTU and JTC conducted feasibility study of the Underground Science City in rock caverns at the Kent Ridge Park.
2000 – 2003	Singapore constructed a tunnel test facility and conducted a series of large-scale tests in Sweden which successfully contributed to the final validation of the UAF design.
2000	Singapore joined the NATO Underground Storage Working Group under the NATO AC 258 Storage Sub-group, became the Secretary of the Working Group and led the group's work in the area of ground shock.
2000	Singapore joined the Klotz Group, an international body of explosives safety experts working on safety issues associated with the storage, processing, and transport of ammunition and explosives. Current members in the Klotz Group include Germany, the Netherlands, Norway, Sweden, Switzerland, Singapore, UK, and USA.
27 th July 2001	UAF Phase 1 (pilot phase) Completion Blast Ceremony. Then DPM and Minister for Defence, Dr Tony Tan Keng Yam, was the Guest of Honour.
7 th March 2008	Commissioning of the UAF by then Minister for Defence, Mr Teo Chee Hean.
18 th March 2009	Publication of "Geology of Singapore (2 nd Edition)" by DSTA, launched by then PS(DD), MINDEF, Dr Tan Kim Siew.

Personal Reflections on UAF Chapter By Zhou YingXin

The opportunity to be involved in the UAF project was a once-in-a-lifetime opportunity. Not the least because it was the very first large-scale rock cavern project in Singapore, and an underground ammunition storage facility built in a highly urbanised city state.

I grew up in China and was trained as a mining engineer. When I first came to Singapore in 1991 after completing my PhD in mining engineering in the USA, Singapore seemed like the most unlikely place for a mining engineer. Yet it is in Singapore that I have found an area where I can put my training in mining engineering to good use. Here we do not have gold or diamonds to mine, but we mine something equally precious – space. After completing my three-year contract with NTU as a research fellow, I wrote to the then LEO about job possibilities. Soon I realised that LEO did not need PhDs for its work, much less a PhD in mining engineering. When Mr Lim Chee Hiong and Mr Ong Yew Hing from LEO met me earlier, they were only interested in discussing possible consultancy work. So, when I was asked to interview for a job later, I was surprised. At the interview, they told me about the plan to study underground ammunition storage. This turned out to be a perfect match for both sides. The final round of my job interview was with the then CDS Prof Lui Pao Chuen. Thus began my very enriching career.

My involvement in the UAF project was indeed very challenging and enriching. I was put in charge of the rock engineering and technology development. As the UAF was the first rock cavern facility in Singapore, we had to build up local capabilities in rock engineering almost from scratch. From the early planning stage, we worked with SDC and NTU, where I took part in a feasibility study on rock cavern

construction while working as a research fellow there. We started some R&D projects with the NTU team with the requirements to provide technical support for the project. In LEO, we started recruiting and training our engineers and getting them involved in the R&D projects as part of the capability build-up. We also linked up with experienced consultants and contractors from Sweden and Norway, and brought SDC engineers in early in our study trips and overseas testing.

I remember personally briefing the top management of SDC on our plans and the need for building up the technical competency in rock engineering design and construction. Through this project, we introduced the Norwegian Tunneling Technology to Singapore, and introduced many innovations that helped MINDEF achieve improved productivity, improved safety, and cost savings despite having started the project with little experience. All these eventually propelled MINDEF to become a technical leader in Singapore in the innovative use of rock cavern space. Our technical expertise has also been put to good use in providing critical technical support to various government agencies in recent years.

In our technology development programme designed to address the critical technological gaps, I had the opportunity to work with many experts from Singapore and overseas. I travelled to many parts of the world to discuss collaborations and large-scale testing overseas, and made many friends. I remember bringing my "portable office" for my overseas visits with Mr Lim Chee Hiong, with a colour printer and stacks of plastic transparency sheets to prepare slides for overhead projection to make many presentations on our plans, and for discussions with NATO's UGSWG and the Klotz Group about possible membership for Singapore.

The spirit of collaboration was really incredible, both locally and internationally.

With my mining engineering background, I was appointed the Test Commander when we did our ground shock testing (we invented GST!) in Singapore in 1997. It was still a steep learning curve for me, having no prior experience in explosives testing but my job was made easy with the support and contributions of all parties involved, including LEO, the SAF, NTU, SDC and ST Kinetics.

We partnered experts from the US Army to provide specialist support in ground shock instrumentation and data analysis. The SAF provided explosives for our testing and medics team standing by to respond to any emergencies.

In our large-scale testing in Sweden, we worked with various teams from the Swedish defence agencies and the consultant Carlbro and Castrum, and the contractor PEAB. The Swedish Armed Forces HQ provided the explosives and very nice Swedish 155mm rounds for our testing. In the first major test in the cold winter in December 2000, they even had their army snowmobiles standing by. And in the hot summer in 2001, they had military helicopters standing by to provide any emergency assistance and to put down possible forest fires. The Norwegian' NDEA and the US' DTRA provided support in instrumentation. Members from both the Klotz Group and NATO's UGSWG also provided technical advice and took part in the tests.

One very important lesson that I learned through the UAF project was that safety standards could be changed if we could produce good research work to support the change! This might sound so logical but at the time we were merely followers of international standards. When we were invited to attend a special meeting of the NATO Working Group working on the NATO Safety Manual on Underground Storage, we felt a great sense of achievement and validation of the quality of research work we did. But we

also learned that converting research results into safety standards involved many other less technical input and decisions (some called it committee decisions) that were required to cater to different cultures, backgrounds, and unique conditions of the member countries. Sometimes trade-offs were required in order to satisfy all member nations. So our direct involvement in the NATO Working Group had not only contributed to their work, but also allowed us to write the new safety standards that included our unique local conditions such as our flat terrain, mixed geology and reinforced concrete buildings.

Personal Reflections and Account of Explosive Testing in Sweden

By Dr Karen Chong Oi Yin

Large Scale Validation Tests

I was responsible for numerical modelling of air blast effects in the UAF, and needed to validate our models. I was put in charge of the explosive validation testing and analysis in Sweden for the UAF programme from 2000 to 2002. Our first series of tests was performed in December of 2000. As the tests took place in winter, our Swedish counterparts commented that we were crazy to even contemplate doing the test then. However, it was imperative for us to do the tests or risk delays in constructing the UAF back home. We went ahead with it.

I arrived at Alvdalen in the late afternoon with my colleague Mr Yew Chor Shuen, and it was already pitch dark, and very cold. Alvdalen was to be our home for the three-week test

period. We commenced working the next day with our Swedish counterparts, performing pre-test recording in the wet, cold tunnels. We were later joined by another three engineers, Mr Guah Eng Hock, Dr Seah Chong Chiang and Dr Zhou Yingxin.

The tests were an international collaboration. Prior to the tests, we had worked hard to interest the international community in participating in the tests. A challenge we had was how to obtain good instrumentation data sets, bearing in mind the very harsh blast environment that the instrumentation gauges would be subjected to. We knew that relying on only a single source for instrumentation would put us at risk not getting any data should it fail. The Norwegian Defence Construction Agency (NDCS) and US DTRA fielded additional gauges for the tests, with the understanding that all the test data would be shared. In addition to obtaining electronic data, we worked with



Fragment Collection Process (2001)

the late Mr Arnfinn Jenssen (from the NDCS) to install cantilevers to collect physical effects data. These cantilevers were aluminium poles of different heights, and would bend at different angles when the blast wave hit them, providing additional information on the blast environment. These would be invaluable if the electronic instrumentation were to fail.

Mr Arnfinn Jenssen was our first MINDEF Visiting Scientist in 1997, he shared with us his tremendous experience in protective structure design. During the Large Scale Tests, he took us (five young engineers) under his wing, spending hours with us discussing the results of the tests. Mr Arnfinn Jenssen went on to join us for each of our subsequent tests that we conducted at Alvdalen.

We were extremely lucky with the weather and on the morning of 13th December 2000, the tests involving 10,000kg of TNT went off without a hitch. We got the data that we needed to validate the numerical models. As the tests had implications on explosive storage safety, we invited engineers and scientists from the international explosive safety community including the NATO A/C 258 UGSWG, the Klotz Group and US defence agencies to witness the tests. We worked into the night analysing the data and presented the preliminary results of the tests to the international community the next day. The data we collected was rich, and provided us and the international community with a deeper understanding of the phenomenon and allowed us to validate our UAF design.

Cased Charge Tests and Debris Mapping

In 2001, we went on to perform the tests with real ordnance, in this case, 1,450 155mm artillery rounds, with a total amount of TNT equivalent to 10,000kg. We understood then that the equivalent TNT for cased ammunitions would be less than bare explosives as energy would have to be used to break up the casing into fragments; we needed to establish how

much this equivalent TNT would be. Also, we needed to understand how much fragment transport would be reduced by engineered features in our tunnels, namely, the bends and debris traps. The only data available in explosives safety manuals were vague allusions to reductions that were unquantified. The test was conducted on 5th July 2001.

In August of 2001, I returned to the site with two engineers, Mr Lim Heng Soon and Mr S Santhirasekar to perform debris data analysis. It soon became clear that this was a mammoth task, as our Swedish counterparts had clearly underestimated the effort required to do this fragment mapping. There were only three people from the Swedish Defence Research Agency assigned to work with us. The fragment collection process comprised dividing the 350m long tunnel into sectors, collecting the debris which comprised sand and gravel mixed with metallic casing fragments, washing and sieving the metal fragments from the sand and gravel, and using small hand held magnets to separate out the metal. The fragments from each sector in the tunnel were weighed. The process was manual and back-breaking.

As the team leader, I had to make sure that our Swedish counterparts knew that we were serious about the debris mapping and would complete the work after we had left. By the time we left Sweden on 29th August 2001, we had collected and mapped a total of 2,700kg of steel fragments from the entire tunnel, except for the debris trap directly opposite the test chamber. Our Swedish colleagues collected an additional 3,086kg of steel fragments in a strip in the debris trap. We used volume extrapolation, to estimate the total amount of debris in the debris trap. I was extremely proud of our team work; together, we established the effectiveness of the debris traps in reducing debris hazards. This was important for the validation of our safety design for the UAF. With the success of our fragment data analysis, we went on to

do it again in 2002 for mixed storage of cased ammunitions and propellants. This time, we were better prepared and FOI engaged contractors for the work.



Fragment Mapping for Mixed Storage (2002)

ACKNOWLEDGEMENTS

Engineering Land Systems would not have been possible without the hard work, support and encouragement of many people. General thanks are also due to the teams at DSO National Laboratories (including the Creative Media Branch and Corporate Communications Branch), Army Information Services, MINDEF Communications Organisation, Defence Industry and Systems Office, ST Kinetics and many others – too numerous to name – who have assisted us in one way or another, in the production of this book.

Authors



Mr David Boey Meng-Whye is a former Defence Correspondent at The Straits Times newspaper and long-time observer of the SAF. He holds a Masters in Security Studies and wrote a dissertation on the SAF, supervised by defence analyst Dr Tim Huxley. David has written widely on the SAF and regional armed forces. He accompanied the SAF on four overseas missions and has reported on live-fire exercises in Australia, the US and in the South China Sea. His book on Operation Flying Eagle profiles the SAF's Humanitarian Assistance and Disaster Relief mission in the aftermath of the 2004 Boxing Day earthquake and tsunami. David sits on the MINDEF Advisory Council on Community Relations in Defence.



Dr Javier Ibañez-Guzmán graduated from the University of Pennsylvania with a MSEE on a Fulbright Scholarship. He obtained his PhD from the University of Reading on a SERC-UK Fellowship. In 2011, he was Visiting Scholar with the University of California, Berkeley, working on connected vehicle applications. He is currently technical manager at Renault S.A., leading work on autonomous vehicle technologies. Formerly, he was Senior Scientist

at SIMTech, where he spearheaded pioneering work on autonomous ground vehicle. He was also adjunct Associate Professor at NTU. He has several publications and patents in the robotics and automotive domains. He is a CEng and a Fellow of the Institute of Engineering Technology (UK).



BG (Ret) Jimmy Khoo is the Managing Director of Singapore District Cooling, a key subsidiary of the Singapore Power group. He is a Senior Vice President who has held various senior appointments in the group. Prior to joining the Singapore Power group in 2007, he was with the SAF and held the post of the SAF's Future Systems Architect (FSA) from 2003 to 2007. He was the first FSA to head the Future Systems Directorate (FSD) and was concurrently a board member of DSTA and DSO. As FSA, he played a crucial role in championing and catalysing the 3rd Generation SAF's transformation effort through concept exploration and experimentation. He holds a BA (2nd Class Hons) in Philosophy, Politics and Economics from Oxford University and an MSc in Management from Stanford University.



Dr Karen Chong Oi Yin is Head Engineering (Protective Systems Engineering) at DSTA. She drives R&D efforts in Protective Engineering for buildings and infrastructure, and has extensive experience in explosives testing, protective systems design and blast modelling and analysis. She was a recipient of the Defence Technology Prize Team (Engineering) Award in 1999, 2006, 2007 and 2011. She graduated with a BSc (Nuclear Engineering) from Queen Mary College, University of London, UK in 1986. She obtained a PhD (Nuclear Engineering) from Queen Mary and Westfield College, University of London, UK in 1991.



Mr Kenneth Quek Keng Ngak graduated from Queen's University Belfast, UK in 1990 with an Honours (Second Upper) degree in Mechanical Engineering and an MSc (Gun System Design) from Royal Military College of Science, UK in 1995 under the Defence Technology Training Award. In 1991, he joined then DMO, MINDEF as a Defence Engineer and began work on artillery and naval weapon systems. In 2006 to 2010, he served as the First Secretary in the Singapore Embassy in Washington DC, USA as the Assistant Head of Defence Technology Office, responsible for technology collaboration with US DoD and DoE agencies. He is the manager responsible for the acquisition and development management of the Pegasus Lightweight Gun Howitzer, High Mobility Artillery Rocket System and Peacekeeper Protected Response Vehicle. He is currently serving in DSTA as a Programme Manager.



Mr Koh Weng Kin graduated from University of Singapore in 1988 with a degree in Mechanical Engineering. In that same year, he joined then DMO, MINDEF as a Defence Engineer and began work on artillery and naval weapon systems. He further obtained a MSc (Gun System Design) from the Royal Military College of Science, UK in 1992 under the Defence Technology Training Award. He was the Programme Manager for the local development of the Singapore Self-Propelled Howitzer. He is currently serving in DSTA as Head Capability Development.



Mr Lai Chun Loong is currently Corporate Advisor to Temasek International Advisor Pte Ltd. He started his career at CIS in 1968 and rose to become its Managing Director from 1983 to 1989. Concurrently he was Managing Director of Singapore Technology Corporation Pte Ltd.

He was appointed President of CIS in 1989. In 1993, he moved to head Sembawang Industrial Pte Ltd, serving as its Deputy Chairman and President. He was the founding Chairman of the Vietnam-Singapore Industrial Park (VSIP) in 1996 and assisted to bring foreign direct investments into VSIP and other business sectors in Vietnam. For his contributions to Vietnam, he was awarded the Friendship Medal by the President of Vietnam in 2006. Mr Lai served in numerous community positions over the past 35 years and is currently a Patron of Clementi Constituency. He served as a member of the Management Council of the German-Singapore Institute from 1982 to 1989, and a member of the Board of Governors of the Singapore Polytechnic from 1983 to 1992. He was awarded a Public Service Medal (PBM) in 1992. Mr Lai graduated with a BEng (Mech) from the University of Auckland under a Colombo Plan Scholarship in 1967. He holds an MBA degree from the University of California, Los Angeles in 1980 and completed the Advanced Management Program at Harvard University in fall 1987.



Er Lee Chuen Fei PBM graduated from the University of Singapore in 1976 with BEng (Mech). He joined CIS in 1978 after completing his full-time NS and was responsible for Engineering Design and Development of ammunition products till 1997. When ST Engineering was established, he progressively served in various capacities (ST Kinetics - including General Manager that established the JV Company – SMART Systems Pte Ltd, Vice President with ST Dynamics, ST Engineering Corporate and ST Marine). He also obtained MSc (Industrial Engineering) and MSc (Management of Technology) from NUS. In 2014, he retired to pursue his own interest and is currently providing consultancy services and training related to Enterprise Risk Management and BCM.



Mr Lee Kah Hoo graduated with a MEng in 1977 from the University of Singapore. He joined CIS in December 1979 as a product development engineer and subsequently took on manufacturing and corporate positions in CIS over the next 20 years. In 1990 he attended the PMD program in Harvard. He left the defence business in 2006 when he was then Director of Corporate Affairs of ST Kinetics. Currently, he sits as an independent director in a company on the Catalyst board.



BG (Ret) Lee Shiang Long was the Head of Joint Communications and Information Systems (HJCIS)/SAF's Chief Information Officer (CIO) from 2006-2013. Before that he was Chief Signal Officer/Army CIO. He was responsible for system architecting, masterplanning and operationalising Integrated Knowledge-based Command and Control (IKC2) for the network-enabled 3rd Generation SAF. He holds a PhD in Mechanical Engineering from Nanyang Technological University, and an MBA from Cambridge University.



Dr Lim Kiang-Wee is the Executive Director of CREATE (Campus for Research Excellence and Technological Enterprise) in Singapore. He graduated from the University of Malaya and obtained his doctorate from Oxford in 1982. He has held academic appointments at NUS and UNSW, Australia. In recent assignments, he has been the Executive Director of SIMTech, IMRE and the Graduate Academy at A*STAR. He set up IPI-Singapore in 2011 to catalyse intellectual property intermediation activities that support and enhance the innovation capacity of Singapore enterprises. He is a member of the Engineering Accreditation Board of Singapore, the Board of Governors of NUS High School and of the Board of Trustees of Singapore Institute of Technology.



Mr Loh Heng Fong graduated from London South Bank University with 1st class Honours in Mechanical Engineering in 1979. He is the Vice President in ST Kinetics, Head of Tracked Mobility Centre and Tracked Vehicle Chief Engineer. He has been instrumental in building up Singapore's tracked vehicle capabilities over the last 34 years. Under his leadership, ST Kinetics has developed highly capable tracked vehicles and armoured defence capabilities for MINDEF and the SAF. As Chief Engineer, he has lent his leadership and technical expertise to the development of platforms such as the AMX-13 SM1, Bionix Infantry Fighting Vehicle, Trailblazer Mine-Clearing Vehicle and Warthog (UK). For his outstanding leadership and contributions to Singapore's defence, Mr Loh was awarded the 2010 Defence Technology Prize Individual (Engineering).



Prof Lui Pao Chuen graduated in 1965 from the University of Singapore with an Honours degree in Physics. He worked as a Scientific Officer of the UK Science Research Council's Radio and Space Research Station in Singapore. In November 1966 he enlisted in the SAF as a Captain on a Short Service Commission and served as Officer-in-Charge of the Test and Evaluation Section, Logistics Division, MID. He became head of Technical Department when it was established in 1968. He was posted to be Head Organisation and Control Department in 1969 and soon after to be deputy of 2PS in SMG. He was the first SAF Postgraduate Fellow and graduated with an MSc in Operations Research and Systems Analysis from the US Naval Postgraduate School in 1973 and appointed Director Logistics Division in 1974 and Special Projects Director in 1975.



Mr Ong Yew Hing is Director (Building and Infrastructure) in DSTA. He started his career in 1984 with then LEO, MINDEF, and has played key roles in the masterplanning, design and development of operational bases and defence infrastructure facilities, as well as in the build-up of protective technology capability within MINDEF. He graduated from Universität Essen Gesamthochschule, Germany in 1982 with a degree in Civil Engineering; and obtained MSc (Civil Engineering) from NUS in 1988 and MSc (Weapons Effects on Structures) from the Royal Military College of Science, UK, in 1989. He is the key delegate representing Singapore in the NATO Underground Ammunition Storage Custodian Group and in the Klotz Group, an international expert group in explosives storage safety.



Ms Rosemary Yeo graduated with a BEng (Mech) from NUS and joined MINDEF in 1983. She obtained an MSc in Gun Systems Design from the Royal Military College of Science, UK in 1991. She started her career working on development of the FH88 guns and subsequently oversaw the development of other armament systems such as the Primus 155mm Self-Propelled Howitzer, the Pegasus 155mm Lightweight Gun Howitzer, the SAR21 Singapore Assault Rifle and the Matador Anti-tank weapon system. She is Director of the Engineering Programme Office in the Public Service Division, spearheading the building of engineering capabilities in the Public Service.



Mr Sia Chong Hean graduated from Singapore University in 1967 with an Honours degree in Physics. He joined the Economic Development Board after graduation as a Senior Officer and was posted to the Industrial Research Unit (subsequently renamed as Singapore Institute of Standards and Industrial Research, SISIR). He was enlisted

for full-time NS shortly. After 12 months of military training, he was posted to MINDEF Technical Department as Technical Officer. On completion of 3 years of NS, he returned to SISIR in 1971. He joined Esso Singapore (now ExxonMobil Singapore) in 1972 and held various posts including managerial positions in Information Systems and Controller's until his retirement in 2007. He has since served in various voluntary organisations including as a chairman of a school advisory board.



Mr Tham Mow Siang graduated in 1965 from the University of Singapore with an Honours degree in Physics. He joined the Civil Service and was appointed Administration Assistant and began his service in the newly established People's Association. He was posted to MID in 1966. He was given the assignment to plan for the establishment of a factory to produce bullets for the SAF. He did the planning for the establishment of CIS and subsequently became its Company Secretary. He had played a central role in the setting up and management of the company. He started Unicorn to market defence products to overseas. He also founded a company, Weichern, in 1974 specialising in steel fabrication, formwork, design and manufacture of conveyors and project management.



COL (Ret) Yun Ta Chun, graduated from the Royal Military College – Duntroon, Australia in 1981 with a degree in Physics and Computer Science. In 1989, he completed his MSc in Computer Science and Information System from NUS. He served as Chief Signal Officer for 7 years, where most of his tenure was focused on modernising the Army in C4I capabilities. After 25 years of service, he founded C3S, bringing to the private sector a wealth of C4I perspectives for real-time, mission-critical businesses. He develops transformational info-comm technology

strategy identifying disruptive technologies to significantly leap frog current operations. This approach addresses more than just improving the efficiency of information management, achieving higher-value functions to attain corporate mission and objectives.



Dr Zhou Yingxin is Head Engineering (Underground Facilities) with DSTA, and Adjunct Associate Professor at NTU. He graduated from the Central South University, China, in 1982 as a mining engineer and obtained his PhD from Virginia Tech, USA in 1988. He joined then LEO, MINDEF in 1994 and played key roles in rock engineering and technology development for the UAF and has been involved in several national initiatives in underground space use. He has also served in various professional leadership positions in local and international societies related to rock engineering and underground space. He is a member of the Editorial Board for the International Journal of Tunnelling & Underground Space Technology.

Contributors

Mrs Agnes Tham
Mr Alfred Tan Boon Thong
LTC Anthony Toh
Mr Chan Chun Wah
LTC Chan Keen Mun
Mr Chua Poh Kian
Mr Fong Saik Hay
COL (Ret) Goh Lye Choon
Mr Henry Cheong Yue Pui
Dr Jake Toh Geok Phuay
Er Lim Chee Hiong
Mr Mah Chi Jui
Mr Peter Seow Tiang Keng
MAJ Png Yan Da
MG (Ret) Ravinder Singh
Dr Richard Kwok
LG (Ret) Winston Choo
Mr Wu Tzu Chien
Ms Yap Lay Hoon

Editor

Prof Lui Pao Chuen

Editorial Support Team

Mr Chua Poh Kian
Ms Surine Ng Pei Gek
Mr Yeo Song Meng



Sitting (left to right)
COL (Ret) Yun Ta Chun, BG (Ret) Jimmy Khoo, Er Lee Chuen Fei, BG (Ret) Lee Shiang Long,
LG (Ret) Winston Choo, Prof Lui Pao Chuen,
Mr Peter Seow Tiang Keng, Mr Koh Weng Kin, Ms Rosemary Yeo, Mr Kenneth Quek Keng Ngak,
Standing (left to right)
Mr Chua Poh Kian, Mr Loh Heng Fong, Mr Richard Kwok, Mr Sia Chong Hean,
Mr Ong Yew Hing, Er Lim Chee Hiong, LTC Chan Keen Mun,
Dr Karen Chong Oi Yin, COL (Ret) Goh Lye Choon, Mr Wu Tzu Chien, Dr Lim Khiang Wee,
Mr David Boey Meng-Whye, Mr Fong Saik Hay
Not in picture
Mrs Agnes Tham, Mr Alfred Tan Boon Thong, LTC Anthony Toh, Mr Chan Chun Wah,
Mr Henry Cheong Yue Pui, Dr Jake Toh Geok Phuay, Dr Javier Ibañez-Guzmán,
Mr Lai Chun Loong, Mr Lee Kah Hoo, Mr Mah Chi Jui, MAJ Png Yan Da, MG (Ret) Ravinder Singh,
Mr Tham Mow Siang, Ms Yap Lay Hoon, Dr Zhou Yingxin

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20. The Straits' Times: page 140

GLOSSARY

Acronym	Description
A*STAR	Agency for Science, Technology and Research
ABMS	Air Bursting Munition System
ACGS	Assistant Chief of General Staff
ACMI	Air Combat Manoeuvring Instrumentation
ACMS	Advanced Combat Man System
ACFR	Australian Centre for Field Robotics
AFV	Armoured fighting vehicle
AGL	Automatic grenade launcher
AHP	Analytical Hierarchy Process
AP	Anti-personnel
APC	Armoured personnel carrier
APFSDS	Armour-piercing fin-stabilised discarding sabot
APFSDS-T	Armour-piercing fin-stabilised discarding sabot - tracer
ART	Air Base Redevelopment Team
ASP	Assistant Superintendent of Police
AT	Anti-tank
BBU	Base bleed unit
BECD	Bases Economic Conversion Department
BG	Brigadier General
BK&P	Bienz, Kummer & Partner of Switzerland
BMS	Battlefield Management System
CAD/CAM	Computer-aided Design and Manufacturing
CAI	Chartered Ammunition Industries
C&E	Communications and Electronics
CCIS	Command and control information system
CD	Civil defence
CDF	Chief of Defence Force
CDSA	Civil Defence Shelter Act
CEP	Circular error probable
CG	Centre of gravity
CID	Criminal Investigation Department
CIO	Chief Information Officer
CIS	Chartered Industries of Singapore
CNC	Computer numerical control
CMPB	Central Manpower Base
CO	Commanding Officer
COL	Colonel
CONOPS	Concept of operations
COTS	Commercial-off-the-shelf
CPoF	Command Post of the Future
CPT	Captain
CSO	Computer Systems Organisation
CVC	Combat vehicle crewman
C2	Command and control
C3	Command, control and communications

C4	Command, control, communications and computers	IOS	Island Ordnance Systems
C4IT	C4 and information technologies	JAUS	Joint Architecture for Unmanned Systems
DBW	Drive-by-wire	JCED	Joint Communications and Electronics Department
DIP	Driver instrument panel	JCISD	Joint Communications and Information Systems Department
DMO	Defence Materials Organisation (1986 to 1996), Defence Materiel Organisation (1996 to 2000)	JTC	Jurong Town Corporation
DoD	Department of Defense, USA	KPI	Key performance indicator
DPM	Deputy Prime Minister	LASS	Lockheed Aircraft Services Singapore
DSO	Defence Science Organisation (pre 1997, now known as DSO National Laboratories)	LAW	Light anti-tank weapon
DSP	Deputy Superintendent of Police	LEO	Lands and Estates Organisation
DSTA	Defence Science and Technology Agency	LCM	Life Cycle Management
DTC	Defence Technology Community	LG	Lieutenant General
DT&E	Development Test & Evaluation	LTA	Lieutenant
DTRA	Defense Threat Reduction Agency, USA	LTC	Lieutenant Colonel
EA	Engineering assistant	LST	Landing Ship Tanks
ED	Engineering Department, CIS	MAJ	Major
EE	Engineering executive	MBT	Main battle tank
EFCSC	Explosives, Fire and Chemical Safety Committee	MC	Maritime Command
EMP	Engineering Master Plan	MG	Major General
ENV	Ministry of the Environment	MGB	Missile gun boat
EOD	Explosive ordnance disposal	MHA	Ministry of Home Affairs
ER	Extended-range	MINCOMM	Ministry of Communications
ERDC	Engineering Research and Development Center, USA	MID	Ministry of Interior and Defence
ERFB-BB	Extended Range Full Bore with Base Bleed	MND	Ministry of National Development
ERFB-HB	Extended Range Full Bore with Hollow Base	MINDEF	Ministry of Defence
eSILK	enterprise System for Innovation, Learning and Knowledge	MMO	Materials Management Organisation
ESTC	Explosives Storage and Transport Committee	MoD	Ministry of Defence, the UK
FCS	Fire control system	MPC	Mobile Patching Centre
FEM	Finite Element Methods	MRT	Mass Rapid Transit
FOI	Swedish Defence Research Establishment	MWO	Master Warrant Officer
FSD	Future Systems Directorate	NATO	North Atlantic Treaty Organisation
GDS	General Diesel Singapore	NEQ	Net explosive quantity
GNSS	Global Navigation Satellite System	NCO	Non-commissioned officer
GPMG	General purpose machine gun	NDEA	Norwegian Defence Estates Agency (previously known as the Norwegian Defence Construction Service)
GPS	Global Positioning System	NFESC	Naval Facilities Engineering Services Centre, USA
GSOA	General Staff Office Automation	NGO	Non-governmental organisation
HADR	Humanitarian Assistance and Disaster Relief	NS	National Service
HEAT	High Explosive Anti-Tank	NSF	Full-time National Serviceman
HEDP	High Explosive Dual-Purpose	NSTB	National Science and Technology Board (the predecessor of A*STAR)
HEST	High Explosives Simulation Test	NTT	Norwegian Tunnelling Technology
HDB	Housing Development Board	NTU	Nanyang Technological University
IA	Immediate Action	NUS	National University of Singapore
ICT	Information and Communications Technologies	OC	Officer-in-Command
IKC2	Integrated Knowledge-based Command and Control	OCS	Officer Cadet School
IFV	Infantry fighting vehicle	ODE	Ordnance Development and Engineering of Singapore (now part of ST Kinetics)
ILS	Integrated Logistics Support	OMP	Operational Master Plan
IMU	Inertial measurement unit	OODA	Observe, Orient, Decide and Act
		OR	Operations Research

ORBAT	Order of battle
OT&E	Operational Test & Evaluation
OVM	On-vehicle material
PC	Platoon Commander
PDF	Peoples' Defence Force
PM	Prime Minister
PLC	Programmable logic controller
PP&P	Plans, Provisioning & Procurement
PRC	Portable Radio Communication
PSA	Port of Singapore Authority
PUB	Public Utility Board
PWD	Public Works Department
Q-D	Quantity-Distance
RAF	Royal Air Force, UK
R&D	Research and development
R/R	Radio relay
RAM	Reliability, availability and maintainability
RMCS	Royal Military College of Science, UK
ROK	Republic of Korea
RSAF	Republic of Singapore Air Force
SA	Singapore Artillery
SADA	Singapore Air Defence Artillery
SADC	Singapore Air Defence Command
SAE	Singapore Automotive Engineering
SAFTI	Singapore Armed Forces Training Institute
SAF	Singapore Armed Forces
SAFTECH	SAF Technical School
SAW	Section automatic weapon
SEAD	Seletar East Ammunition Depot
SEEL	Singapore Electronics and Engineering Limited
SCME	SAF Centre for Military Experimentation
SDC	Sembcorp Design and Construction Pte Ltd
SFI	Singapore Food Industries
SIMTech	Singapore Institute of Manufacturing Technology
SLAM	Simultaneous localisation and mapping
SLWH	Singapore Light Weight Howitzer
SMG	Science and Management Group
SOP	Standard operating procedure
SOR	Specific Operations Requirements
SP	Self-propelled
SPF	Singapore Police Force
SPH	Self-propelled gun-howitzer
SPO	Special Projects Organisation
SSC	Short Service Commission
SSSO	Senior Specialist Staff Officer
ST Kinetics	Singapore Technologies Kinetics
SVA	Singapore Volunteer Artillery
SVC	Singapore Volunteer Corps

SYSCON	Systems control
TCS	Trunk Communications System
TD	Technology development
TEA Section	Test, Evaluation and Acceptance Section
TiO2	Titanium Dioxide
UAF	Underground Ammunition Facility
UHF	Ultra High Frequency
UGSWG	Underground Storage Working Group
UGV	Unmanned ground vehicle
URA	Urban Redevelopment Authority
UK	United Kingdom
VAM	Vehicle Actuation Module
VHF	Very High Frequency
VSEL	Vickers Shipbuilding and Engineering Limited
V2V	Vehicle-to-vehicle
WAOB	Weapons, Ammunition and Optics Base
WI	Work instruction
WWII	World War Two, also referred to as Second World War
XV1, XV2	eXperimental Vehicle 1, eXperimental Vehicle 2
2LT	Second Lieutenant
2PS	2nd Permanent Secretary

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© 2016, Ministry of Defence, Singapore
Published by Ministry of Defence, Singapore
303, Gombak Drive
Singapore 669645

Designed by
Advalanche Integrated Advertising Pte Ltd
114 Lavender Street #03-64
Singapore 338729

ISBN 978-981-11-1490-8

Printed by
First Printers Pte Ltd
203 Henderson Industrial Park
#07-09 Singapore 159546

